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Final Report

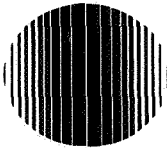
STUDY TO DEVELOP A TECHNIQUE FOR MEASUREMENT OF
HIGH ALTITUDE OZONE PARAMETERS

Prepared for
National Aeronautics and Space Administration
Electronics Research Center
575 Technology Square
Cambridge, Massachusetts 02139
Attention: KI/Instrumentation Laboratory

Contract NAS12-137

EOS Report 7087-Final

12 November 1968



ELECTRO-OPTICAL SYSTEMS, INC.

A XEROX COMPANY

PASADENA, CALIFORNIA 91107 • 213/351-2351



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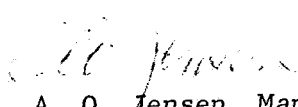
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ELECTRO - OPTICAL SYSTEMS, INC.

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ABSTRACT

Results are presented of a two-year study and research effort to evaluate optical techniques for monitoring the atmospheric ozone distributions on a continuous basis and on a worldwide scale. The conclusions of an analysis of laser techniques for remote probing of the atmosphere for ozone are given, along with a recommendation for further study of one specific technique involving ground-based lasers. The major emphasis of this report is placed on a detailed documentation of the practicality of a passive technique for monitoring ozone from satellites, which relies on the use of the sun as a light source for absorption measurements through the earth's atmosphere. The vehicle chosen for this proposed measurement is the Nimbus meteorological satellite, whose near polar, sun-synchronous orbits would allow excellent coverage of the ozone distributions to be obtained at high latitudes in both hemispheres. The importance of this type of coverage, from the point of view of understanding the complex polar atmospheric circulation patterns, is also treated in some detail.

FOREWORD

This report contains the results of a two year study program which was conducted at EOS for the Electronic Research Center of the National Aeronautics and Space Administration (Contract NAS 12-137). Part I of this report consists of material produced during the first year's effort and which was submitted as the first year interim report (EOS Report No. 7087-IR-1). Part II deals with results obtained largely during the second year of the program effort. The project was performed under the supervision of J. Duardo.

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SECTION 1

INTRODUCTION

Although ozone is present in the earth's atmosphere only as a minor constituent, it has a profound influence on atmospheric dynamics by virtue of the fact that it is an extremely efficient absorber of solar UV radiation. The distribution of ozone in the atmosphere essentially governs the rate of absorption of solar radiation as a function of altitude, latitude, longitude, and solar zenith angle. The resultant atmospheric temperature gradients in turn provide one of the principal driving forces for the atmospheric wind fields. As evidenced by the discussions in this report and the numerous literature articles referenced in the bibliography (Section 9), a great amount of observational data has been compiled concerning ozone distributions at numerous locations. The fundamental principles of the atmospheric circulation-ozone distribution interrelationship are well understood. However, in order to extend this knowledge and to provide a means of tracing the atmospheric circulation on a global scale, measurements of the ozone distribution should be performed on a continuous basis with worldwide coverage.

The atmospheric ozone content and its vertical distribution have been measured by optical techniques since Fabry and Buisson first demonstrated in 1913 that ozone was responsible for the atmospheric solar cutoff at $3000\text{\AA}$. Since then, a great number of spectroscopic investigations of the absorption properties of ozone have also been

conducted in the laboratory. As a result of the laboratory measurements, the numerous and extensive measurements of atmospheric concentrations, and the thorough analyses which have been performed in the reduction of observational data, the optical techniques for determining total ozone concentrations have been highly refined. The resolution with which the vertical distribution of ozone can be determined from the ground is still, however, rather poor. Among the major objectives of this program is the determination of how the established optical techniques for measuring the vertical distribution of ozone can be adapted so they can be performed from an orbiting satellite. The limits of accuracy for these techniques are also to be established by analyses which adopt reasonable values of anticipated measurement errors.

The studies performed to date on this program have confirmed the basic feasibility of using optical means for the continuous measurement of atmospheric ozone from an orbiting satellite. Two techniques, in particular, appear to offer great promise for implementation in the near future. That is, it is not anticipated that a long instrument, or device, development period would be required for the utilization of these two techniques aboard orbiting spacecraft. The principles of these techniques are discussed in some detail in Sections 6 and 7 of this interim report. Discussions and evaluations of these techniques are presented in this report.

Another program objective is to evaluate the optical techniques for their ability to determine wind motion in the upper atmosphere. In particular, major emphasis will be placed on the feasibility of utilizing the optical techniques to monitor ozone-air mass motion from the equator to the poles. In this connection, the theories which have been advanced concerning the use of ozone as a

tracer for wind motion have been reviewed and are discussed in detail in Section 2.

These theories are being critically analyzed since they will prove to be major considerations in the fulfillment of another of the program requirements, namely, to recommend the optimum satellite orbits and positions of supporting ground stations for the attainment of information concerning atmospheric winds. This task will be performed in the forthcoming second-year effort.

During the period covered by this report, a major effort was expended in compiling and evaluating a comprehensive bibliography of articles relating to the absorption properties of ozone and to optical techniques for measuring the concentrations of atmospheric ozone. The contents of these articles served as a basis for selecting the optical techniques which offer the greatest promise for the atmospheric ozone measurements. The large number of articles which have been published in this field justifies their inclusion, in the form of a list of references, as a separate section of this report. Accordingly, Section 9 contains a bibliography of ozone articles classified according to whether the primary emphasis is on atmospheric photochemistry, atmospheric dynamics, spectroscopic properties, or the determination of atmospheric concentrations. Sections 3 and 4 of this report summarize the information, obtained from the articles on ozone spectroscopy and atmospheric measurement, that is pertinent to the analyses being performed during the present program.

SECTION 2

METEOROLOGICAL ROLE OF ATMOSPHERIC OZONE

Although the total amount of ozone in a vertical column above the earth's surface corresponds to only about 0.3 cm when reduced to standard temperature and pressure (STP), this chemical species exerts a powerful influence on meteorological processes, principally by virtue of the high efficiency with which it converts incident solar ultraviolet radiation into heat. This can be illustrated, superficially, by considering that a nonuniform distribution of ozone in the earth's atmosphere, and the resultant nonuniform heating, will lead to temperature gradients which can in turn create atmospheric wind fields. However, a redistribution of ozone by atmospheric winds will lead to an alteration of the temperature and wind patterns so that a complex relationship between ozone distribution and wind patterns can generally be expected.

The objectives of the discussions appearing in this section are:

(1) to demonstrate the intimate role that ozone plays in meteorological processes, with special emphasis being placed on atmospheric wind-ozone relationships, and (2) to establish the value of continuous monitoring of the worldwide distribution of ozone for the purpose of tracing large scale air mass motions and simultaneously obtaining information concerning other meteorological parameters.

2.1 PHOTOCHEMICAL PRODUCTION OF OZONE

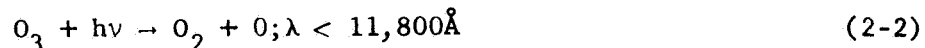
A consideration of the photochemical processes in the earth's upper atmosphere which are responsible for the ozone content is important for the following reason: The transport and circulation of ozone by atmospheric winds was first recognized as an important process when the measured vertical ozone distributions were found to deviate from those which had been predicted by photochemical theory. For this reason, a brief review of the photochemistry which results in the formation and destruction of atmospheric ozone is presented here.

Since Chapman^{1*} first outlined the principal features of the photochemical processes involved in the creation of atmospheric ozone, several analyses have been performed to determine the ozone content that would be anticipated on the basis of photochemical equilibrium. Although these latter analyses take into account factors not included in the original theory, the general scheme as presented by Chapman nevertheless remains valid.

Recent reviews of the photochemical production of atmospheric ozone have been published by B. G. Hunt^{2,3} and by Whitehead, et. al.⁴

The latter authors considered only those photochemical reactions which would occur in an atmosphere of ozone (O_3) and atomic and molecular oxygen (O and O_2) in the presence of inert third bodies.

The most important of these reactions are considered to be:



*See Section 9.6 for cited references

where M is any third body, presumably N_2 in most cases.

The additional reactions



are not considered to significantly affect the equilibrium concentrations of ozone.⁵

The quantities required for a numerical calculation of the equilibrium amounts of atmospheric ozone due to the above photochemical reaction scheme are: (1) the flux of solar radiation within the pertinent wavelength bands that is incident on the top of the earth's atmosphere, (2) the absorption cross-sections per molecule of O_2 and O_3 in the pertinent wavelength bands, (3) the values of the rate coefficients, k , for the above reactions, (4) the density distribution with altitude of O_2 and N_2 . In addition, the solar zenith angle must be taken into account.

Reasonably reliable values for the solar radiation flux are now available as a result of rocket measurements. The absorption cross-sections of both ozone and molecular oxygen have been carefully measured. There exists some question, however, as to the cross-section value of O_2 that should be used in the ozone calculations, since absorption by oxygen is known to be pressure dependent.⁶ The rate coefficients are difficult to measure in the laboratory, and, moreover, some of them are strongly temperature dependent. So-called standard distributions are usually employed for the densities of air molecules. In spite of the necessity for adopting values of these parameters that are somewhat uncertain, there is no doubt about the photochemical origin of ozone.

The calculation of equilibrium amounts of ozone has been performed by various investigators including Paeltzold,⁷⁻¹² Nicolet,¹³ Frenkiel,¹⁴ Craig,⁶ Blamont and Donahue,¹⁵ Chapman,^{1,16} Wulf and Deming,¹⁷ and by Whitehead, et. al.⁴ Although the calculations performed by these different authors differ in such details as the values assumed for the above-named reaction parameters, all are in general agreement with the following conclusions:

1. The amounts and vertical distributions of ozone in the upper stratosphere can be accounted for by the existence of an equilibrium among the photochemical reactions (2-1) through (2-5).
2. The ozone content of the lower stratosphere cannot be accounted for by in situ photochemical production, but must have its origin in the upper stratosphere. It is presumably formed in the photochemical equilibrium region (above about 40 km) and transported by vertical wind motions to the lower stratosphere, where it is relatively protected from photodecomposition.
3. No significant diurnal variation in the total ozone content is anticipated on the basis of the photochemical reaction scheme. In particular, no significant changes in the total ozone content are expected to occur during the night when the sunlight is absent. Although the concentrations in the uppermost layers may change during the night, the amount of ozone in these layers represents only a small fraction of the total ozone.
4. Minimum amounts of total ozone should be associated with large solar zenith angles. This follows from the fact that the path length for a solar ray through any given layer becomes greater as the zenith angle increases. This results in a proportionately greater absorption of solar radiation in the upper layers and a decrease in the intensity incident on the lower layers. The net effect is to reduce the equilibrium concentrations of ozone.

Whereas the investigators cited above considered only the five listed reactions, Hunt,^{2,3,18} Hampson¹⁹ and Roney²⁰ also included a set of reactions involving H_2O , OH and HO_2 . By adopting improved values of k_3 and k_4 given by Bensen and Axworthy and the value of k_5

determined by Reeves, Mannella, and Harteck,²¹ Hunt also concludes that the atmospheric concentrations of ozone above about 40 km are consistent with photochemical theory. He attributes the fact that other investigators have previously arrived at this conclusion by considering only reactions 2-1 through 2-5 as being due to a fortuitous choice of erroneous values for k_3 , k_4 , and k_5 . The errors in the assumed values just offset the error in ignoring the reactions involving hydrogen-containing compounds, according to Hunt. In any case, it is generally accepted that the ozone concentrations in the upper portion of the ozonosphere are in accord with the photochemical reaction mechanisms defined by Chapman.

2.2 OBSERVED OZONE DISTRIBUTIONS

The ozone distributions of interest are: (1) Variations in the total (integrated) amount of ozone in a vertical column (of unit area cross-section area) which extends upward from the earth's surface through the entire atmosphere. These include diurnal, daily and seasonal variations over any given location, as well as latitudinal and longitudinal variations at any given time. (2) The vertical distribution of ozone content with altitude, i.e., the vertical profile, which also exhibits temporal and geographical fluctuations. These two types of distributions are measured by different methods and, in general, much more extensive data are available concerning variations in the total ozone content than variations in the vertical distributions.

2.2.1 VARIATIONS OF TOTAL OZONE CONTENT

Craig⁶ in 1950 summarized the results of total ozone measurements that had been obtained until that time. Substantial additional data have become available since 1950, and especially during the IGY.

These were summarized in 1960 by Godson²² as shown graphically in Fig. 2-1. The solid contours in this figure describe the mean distribution of total ozone (in 10^{-3} cm NTP) as a function of month and latitude in the Northern Hemisphere. The amounts shown were arrived at after considerable averaging over a large number of observations and smoothing of data were performed. Several features of the observed variations in total ozone content are conveniently illustrated by means of this figure. It is seen that the total amount of ozone is a maximum in spring and a minimum in autumn with the largest amplitude of variation at high latitudes. There is also very little seasonal variation in the vicinity of the equator, with only a slight maximum being observed in the late spring or early summer. During most of the year, the total amount of ozone increases from the equator to a maximum at about 60°N. In the spring, the maximum occurs at or near the pole. It is to be noted that the observation of a spring maximum at the pole is in disagreement with conclusion (4) of Subsection 2.1, which was based on photochemical considerations. This observation was instrumental in pointing to the importance of atmospheric mass motions in redistributing the photochemically produced ozone from the equator to the poles (see subsection 2.3.1). (Relatively fewer measurements of the total ozone content have been made in the Southern Hemisphere. However, the measurements that have been made indicate that the seasonal and temporal variations in the two hemispheres are quite similar.^{23,24})

Evidence for longitudinal variations in the Northern Hemisphere has been given London^{25,26} who observed that at all seasons there is more ozone over eastern North America, eastern Asia and central Europe than at other longitudes. These differences become especially pronounced in spring. Kulkarni, et. al.,²⁷ have noted the amounts of ozone at Tateno, Japan (36°) are consistently larger than at

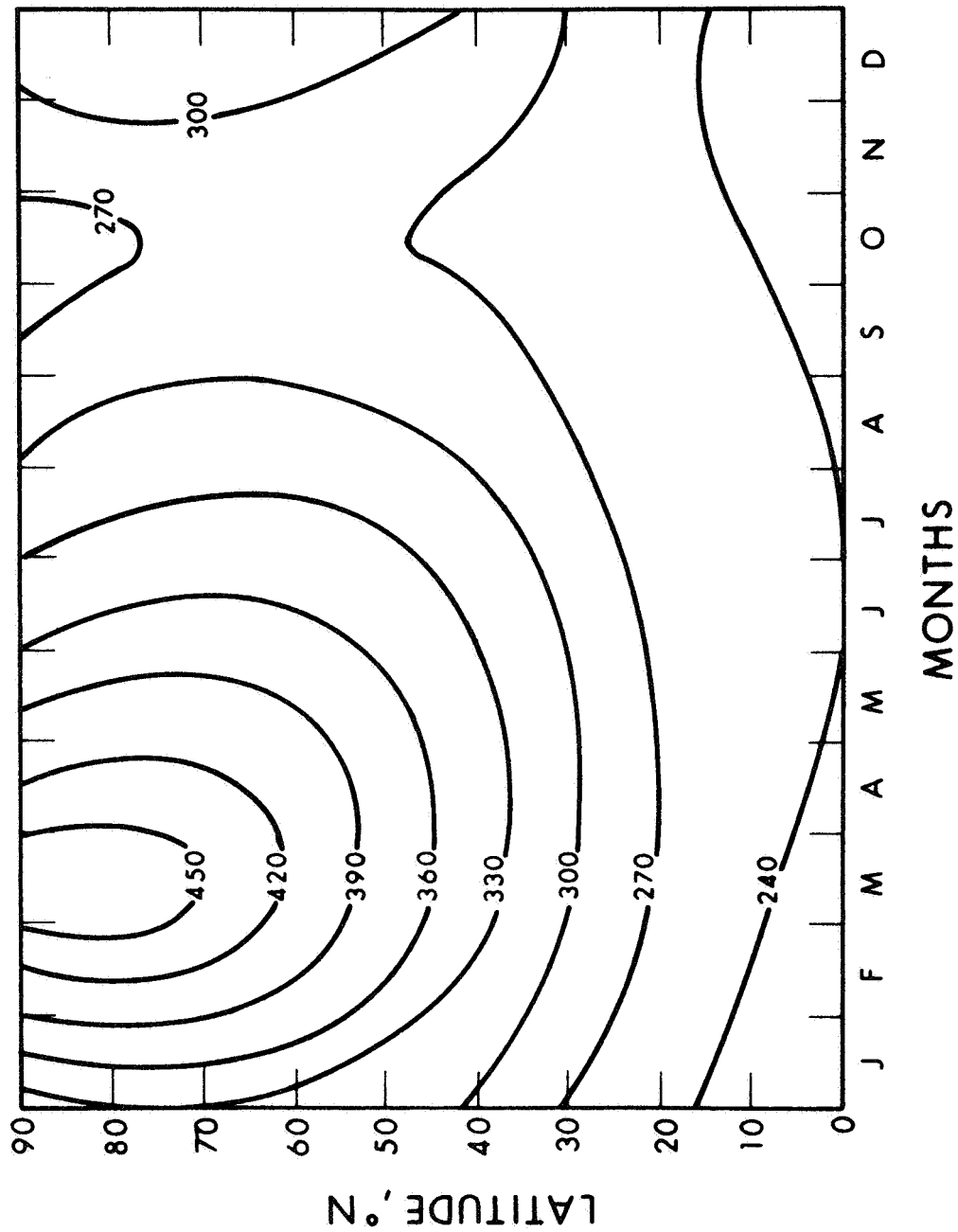


Figure 2-1. Mean Distribution of Total Ozone (units) as a Function of Month and Latitude (Godson, 1960)

Srinagar, India (34°N), particularly during the late winter and spring.

Temporal variations include long-term fluctuations, e.g., month-to-month, and the shorter term fluctuations which are superimposed on these, such as, for example, day-to-day fluctuations. Perl and Dutsch²⁸ have published extensive data concerning the annual variation of total ozone over Arosa, Switzerland which were obtained during a unique series of measurements made between 1926 and 1958, with minor interruption. These data allowed long-term average values to be determined for each calendar month. These average values appear in Fig. 2-2 as circle points.

The vertical lines shown attached to the points in the figure represent the root-mean-square values of the deviations of individual monthly means from the long-term mean for each month. It is seen that these deviations can be rather sizeable, amounting to 23×10^{-3} cm NTP in February, for example. The deviations for June through November, on the other hand, range from 10 - 12×10^{-3} cm NTP. In addition to the monthly and annual variations there occur large and striking deviations of individual daily values from the monthly mean. As noted by Craig,²⁹ the Arosa data can be used to compute the deviation of each daily value from the mean for the month in which it occurs. For the month of March, the root-mean-square value of such deviations from 1949 through 1958 was 33×10^{-3} cm NTP, and for the month of October 16×10^{-3} cm NTP. The daily deviations are such that it is not unusual for individual daily values of total ozone in autumn to exceed certain individual values during the period of spring maximum. The types of deviations observed at Arosa are considered by Craig³⁰ to qualitatively represent the behavior at all locations not too near the equator, with variations at higher latitudes being even more pronounced.

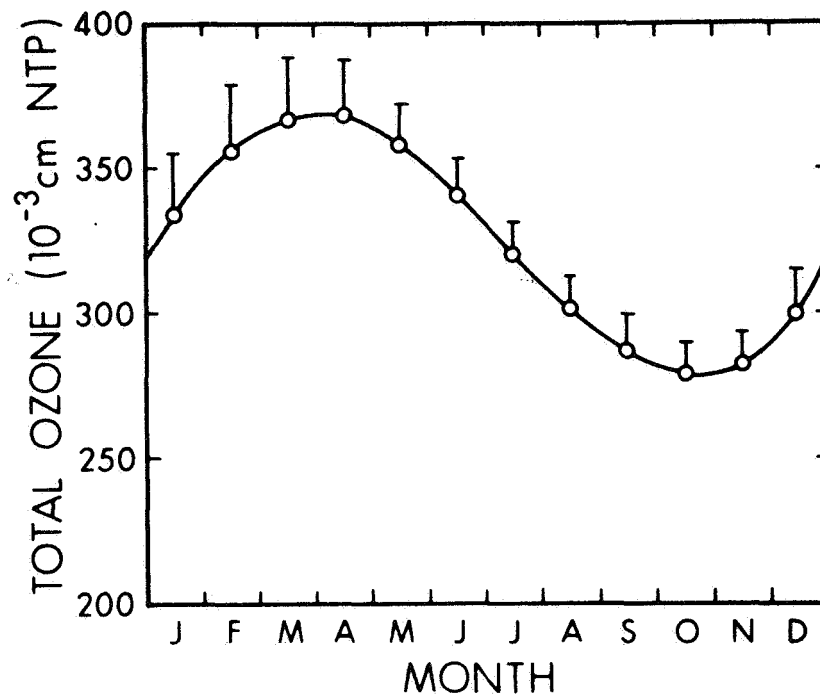


Figure 2-2. Annual Variation of Total Amount of Ozone at Arosa, Switzerland (Perl and Dütsch, 1959)

The above discussions serve to illustrate the types of variations of total ozone content that are known to occur. The data discussed, of course, applies only to the times and locations cited in the examples. However, these examples emphasize the fact that the total ozone content at any given location can only be determined at a given time by direct measurement; the actual amount may differ markedly from mean values.

2.2.2 VARIATIONS IN VERTICAL OZONE DISTRIBUTION

Marked temporal and geographical variations also characterize the vertical distribution of ozone. Figure 2-3 shows five vertical distributions as determined by Mateer and Godson³¹ from observations at Moonsonnee and Edmonton, Canada, during different seasons. The vertical profiles were computed from Umkehr data (see section 4) which does not allow the distributions to be determined with great resolution and necessarily smooths out small-scale features. However, the principle features shown in the figure are typical of all vertical ozone distributions which have been observed at high latitudes. The maximum density of ozone is found in the lower stratosphere, usually between 15 and 30km. The ozone density above 30km decreases rapidly with height. Below the tropopause, i.e., below approximately 10 km, the ozone density is small and relatively constant. Of special importance is the fact that variations of total ozone amounts are mainly accounted for by variations in the lower stratosphere.

Dütsch³² has published similar seasonal curves for Aroza, Switzerland, which is situated at a lower latitude than the Canadian stations. As is seen in Figure 2-4, the vertical distribution and its seasonal variation at Aroza is qualitatively the same as at the higher latitudes. One notable difference is that the seasonal variations in the lower stratosphere are smaller. In the figure there is also shown a vertical distribution which was measured at Leopoldville in the Congo. As

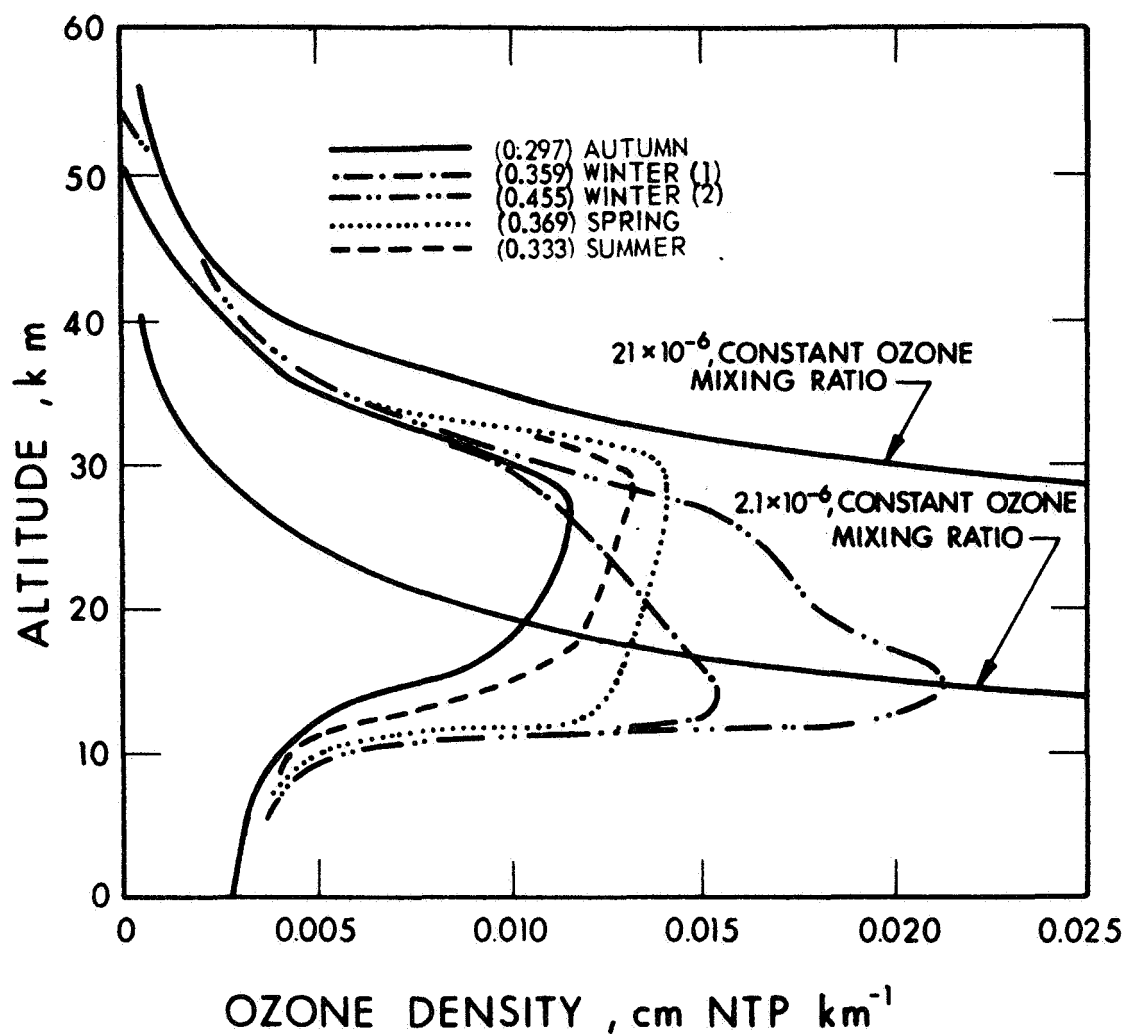


Figure 2-3. Average Vertical Distributions of Ozone at Moosonee and Edmonton, Canada, for Different Seasons of the Year (Mateer and Godson, 1960)

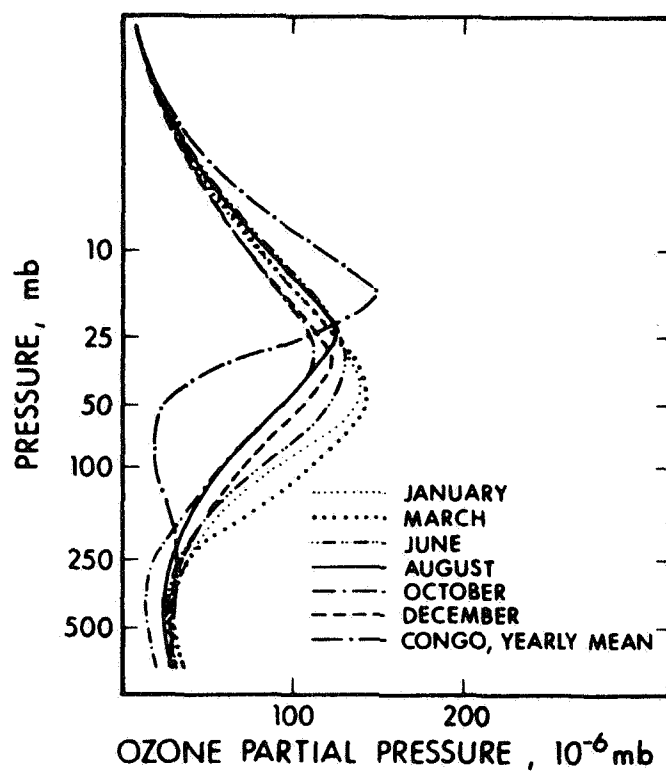


Figure 2-4. Average Vertical Distributions of Ozone at Arosa for different Months of the Year (Dutsch, 1962)

in most measurements made near the equator, there is little seasonal variation at any altitude and the maximum density occurs at a higher altitude.

The above examples show that there is a direct correlation between seasonal variability in the vertical distributions and in the total ozone amounts. This is due to the previously noted fact that changes in total ozone amounts are due mainly to changes in the ozone concentrations in the lower stratosphere. It will be seen in later discussions that this variability is governed by transport mechanisms involving large-scale atmospheric wind motions.

One feature of vertical ozone distributions which is not shown in Figs. 2-3 and 2-4, is the tendency for the occurrence of double maxima in the vertical profile on days of large total amounts of ozone. That is, when the integrated ozone content is unusually large, a primary maximum in concentration is observed between 20 and 35km, and a secondary maximum between 10 and 20km. The existence of the second maximum was first suggested by Gotz³³, and then later confirmed by Ramanathan and Karandikar³⁴. From observations at Tromso, Tronsberg and Langlo³⁵ also obtained evidence for a double maximum. Durand³⁶, et.al., deduced two marked maxima at 17 and 25KM from the data from a V2 rocket flight over New Mexico in October 1947. Regener³⁷ has also observed double maxima in the results of balloon flights over New Mexico. Normand³⁸ has shown that the secondary maximum, if analyzed in terms of the ozone-to-air mixing ratio, can provide valuable information concerning the vertical component of stratospheric winds. (see Subsection 2.3.1)

2.3 EVIDENCE FOR TRANSPORT OF OZONE BY ATMOSPHERIC WINDS

Three types of arguments or evidence have been advanced to establish the value of monitoring ozone distributions over wide areas as a means of

tracing atmospheric winds. These are: (1) an argument based on the observed deviations of ozone distributions from those predicted by photochemical theory, (2) analyses, including numerical computations, which show that non-uniform distributions of ozone in the atmosphere will result in differential heating and, therefore, temperature gradients of sufficient magnitude to cause air mass motion, and (3) observational data which provide direct correlations to be made between ozone distributions and atmospheric wind fields which are simultaneously measured.

In order to illustrate the value of continuous ozone monitoring as a means of providing information about air mass motions, the three types of evidence mentioned above will be reviewed here.

2.3.1 DEVIATION OF OZONE DISTRIBUTIONS FROM PHOTOCHEMICAL EQUILIBRIUM PREDICTIONS

The first type of deviation to be noted was discussed in Section 2.1, where it was stated that the ozone concentrations in the lower stratosphere did not agree with equilibrium predictions. In addition to failing to predict the correct absolute concentrations, the photochemical theory cannot account for the great variability observed in the lower stratospheric ozone content. It is only by invoking a combination of vertical air displacements and horizontal advection* that the observed concentrations, and their variations, can be reconciled with photochemical theory.

The effect of a vertical component of air flow on the vertical profile depends not only on the original ozone distribution, but also on the photochemical stability of ozone at the level in question.

* The horizontal shifting of a mass of air, considered especially as a means of transfer of heat.

Wulf and Deming¹⁷, Nicolet¹³, Craig⁶, and Dütsch³⁹, among others have examined the stability or life of ozone, i.e., the efficiency with which the photochemical processes at any given level will respond to a perturbation due to winds, etc., to restore the ozone content to its equilibrium value. The main conclusion from these studies is that the times for half restoration is of the order of hours or less for levels above about 35km, but may be weeks or more below 20km (due mainly to the low efficiency of O_2 and O_3 dissociation at the lower altitudes). Dütsch³⁹, for example, concludes that the photochemical time constants may vary from minutes at 55km to years at 20km. Wulf and Deming¹⁷ arrived at similar conclusions and used these to show that if a parcel of air containing ozone is transported, for example, from the altitude at which the amount is in photo-equilibrium with solar radiation to a level considerably above this, the solar radiation rapidly reduces the ozone content to the equilibrium amount at this latter level. However, if this ozone is transported to a level considerably lower than that of the maximum concentration, it is appreciably screened from the action of solar radiation. At the same time, the deficit of ozone at the point from which it was transported downward is rapidly restored by photochemical action. This observation has led to the widely accepted conclusion that downward movement of air in the stratosphere will lead to an increase in total ozone while upward movement of air will tend to bring ozone to a minimum amount.

Normand³⁸ made the very significant observation that the ozone mixing ratio (not density) in the lower stratosphere is a conservative property of a parcel of air and is determined mainly by the past history of that parcel of air. Along an isobar in the lower stratosphere, the ozone mixing ratio should increase in subsiding air and decrease in ascending air. Normand also notes that the secondary maxima in the vertical tend to occur on days of high total ozone content and that

if the ozone were plotted in terms of its mixing ratio vs altitude, the secondary maxima would appear as a change of slope on the curve. He concludes that if the vertical distribution of the mixing ratio were known from day-to-day over a large area, valuable information would be obtained concerning the vertical component of wind in the lower stratosphere. (Special note is taken of this conclusion at this point, since the optical technique which is recommended in Section 6 allows the simultaneous measurement of ozone and air concentrations, i.e. the mixing ratio, to be determined as a function of altitude.). Reed⁴⁰ demonstrated that measured atmospheric vertical displacements are of sufficient magnitude to at least partially account for the day-to-day fluctuations in both the total ozone content and its vertical distribution. Figure 2-5 shows the results of a sample calculation performed by Reed, which illustrates the extent to which the vertical profile of the ozone mixing ratio can be altered by allowing vertical displacements to operate on an assumed initial distribution. Curve I in the figure represents an initial distribution which corresponds to a total ozone amount of 0.132 cm (NTP). This latter curve is allowed to be displaced downward by a distribution of vertical velocities resulting in the new distribution represented by Curve II. The length of the ordinates between the two curves indicates the assumed displacements. Not only is the vertical distribution altered, but, with the assumed displacements, the total ozone content increases from 0.132 cm to 0.156 cm. Reed concludes that this increase of 0.024 cm is close to the theoretical maximum that can be accounted for when the magnitude of known vertical motions is considered. Larger increases than this can be explained only by assuming that horizontal advection also contributes to the increase.

The discussions of this subsection up to this point have emphasized the discrepancy between observed vertical ozone distributions and those predicted from photochemical theory. Equally significant, as

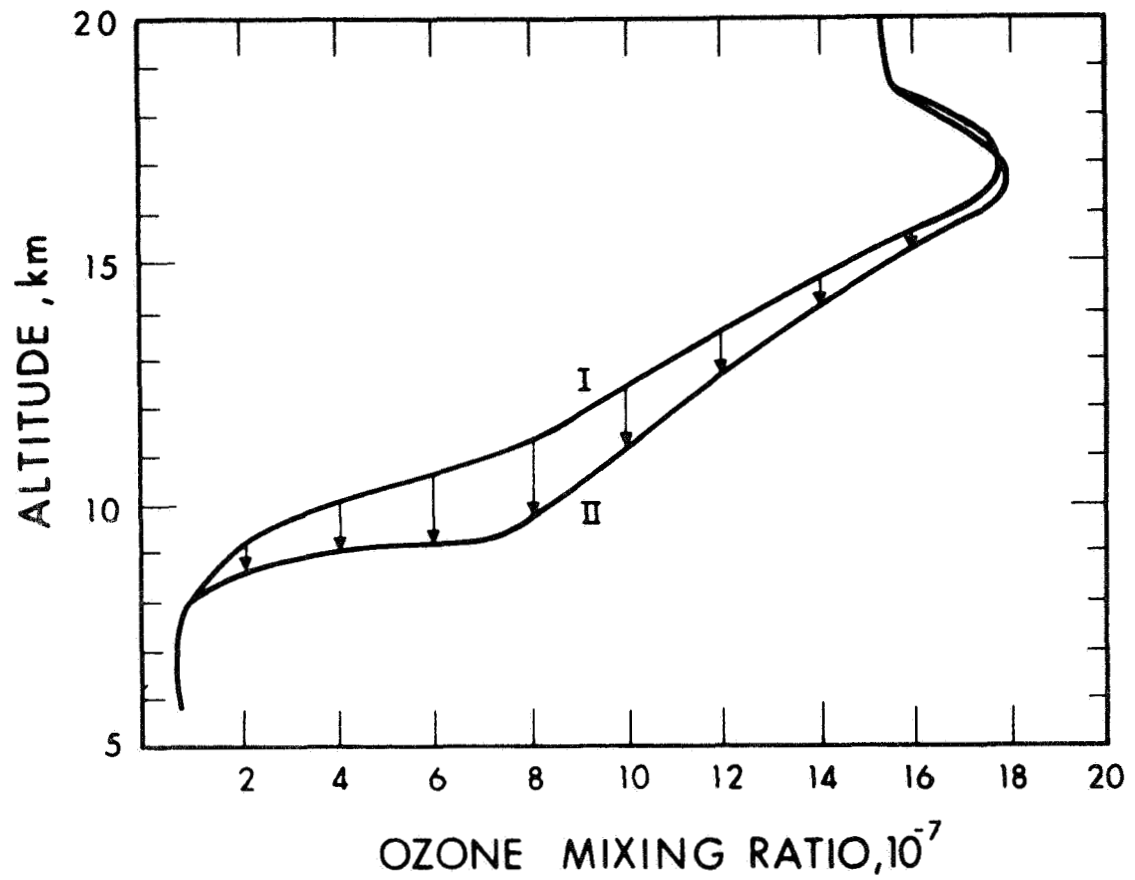


Figure 2-5. Alteration in Mixing Ratio Vertical Distribution Caused by Vertical Displacements (Reed, 1950)

indications of the importance of ozone redistribution by atmospheric motions, are the discrepancies between the observed latitudinal ozone distributions and those predicted by theory. As was noted in Subsection 2.2.1, the occurrence of a maximum in the total ozone content over polar regions in the spring was in contradiction to conclusion (4) of the photochemical discussion (subsection 2.1). Craig⁶, among others, has pointed out that neither the latitudinal nor the seasonal variations of ozone concentrations could be explained in terms of variations in the solar zenith angle. Wulf⁴¹ was apparently the first to point out that the spring polar maximum could be explained in terms of a general circulation pattern which includes both vertical transport and a meridional component of circulation. This pattern is illustrated in very simplified form in Fig. 2-6, in which the ozone density is schematically represented by the dark shading. Wulf pointed out that the meridional circulation pattern illustrated in the figure was consistent with the known temperature distribution in the stratosphere. The meridional component causes air to descend in the atmosphere over the equator and to move northward in the lower stratosphere. At the poles the stratospheric air would rise again, while the tropospheric air would descend in the manner shown in the figure. Air rising over the poles would have its ozone sharply reduced by solar radiation, while air descending over the poles would lead to a large concentration of ozone in the cold arctic air. As this air works its way southward over the earth's surface, the ozone content will diminish to an extent which depends on the amount of contact with the surface. Meanwhile, the air rising over the equator will be relatively free of ozone because of solar action, which ensures the integrated amount of ozone will be a minimum in this region. Kellogg and Schilling⁴² have elaborated somewhat on Wulf's proposed circulation pattern, showing that the general pattern agrees with a large number of observational results and theoretically deduced features of the upper atmosphere.

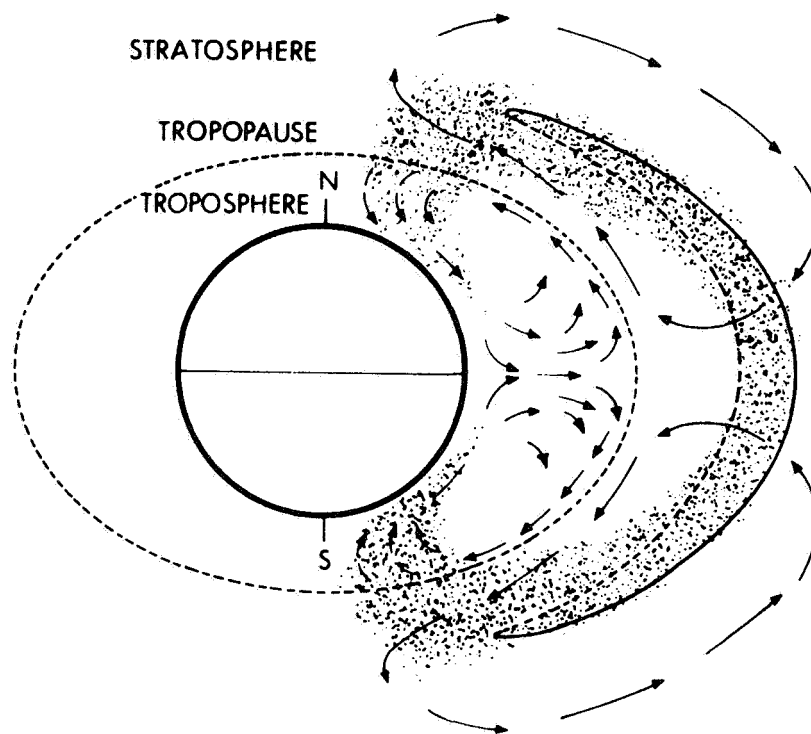


Figure 2-6. Atmospheric Circulation Pattern Leading to Latitudinal Redistribution of Ozone (Wulf, 1945)

While Wulf's circulation pattern is now widely accepted, there is some question as to the relative importance of horizontal and vertical motions in explaining variations in ozone distributions at any given time and place. Paetzold⁴³ concludes that spring fluctuations are dominated by vertical motions and mixing. Ramanathan⁴⁴ states that ozone variations associated with weather systems are most marked in the period October to June. Goody and Roach's⁴⁵ results of ozone IR emission measurements tend to confirm that fluctuations in total ozone amount are not due to the same causes at all seasons. Others who have discussed observed ozone distributions and/or have attempted to evaluate the relative importance of horizontal and vertical motions are cited in References 46 through 70. There is unanimous agreement among all authors who have investigated this problem about the need for a greater amount of observational data with which to compare the results of theoretical analyses and computations.

2.3.2 HEATING DUE TO OZONE ABSORPTION AS A DRIVING FORCE FOR WINDS

The discussion in the preceding subsection was intended to demonstrate the manner in which ozone photochemical considerations and atmospheric circulations could account for the observed ozone distributions and their variations. In actual fact, the problem is much more complicated, since the atmospheric distribution of ozone is one of the principal factors governing the magnitude and direction of atmospheric mass motions. In analyzing the response of the earth's atmospheric circulation to the solar heat input in the stratosphere, Webb⁷¹ considers the distribution of ozone to be the most important variable, aside from the simple geometry of the sun-earth relationship and possible fluctuations in the solar UV flux.

The role that ozone absorption plays in the general circulation pattern can be illustrated in simplified form as follows: During the equinoctal

period, when the sun's incident radiation is perpendicular to the earth's surface at the equator, there exists considerable symmetry between two hemispheres, with respect to the angle of incidence of solar radiation. In particular, the input of solar energy into the upper atmosphere is symmetric in both directions away from the equator, if it is assumed that the opacity is uniform. This latter assumption implies identical latitudinal distributions of ozone in the two hemispheres. Ultraviolet radiation of a given wavelength should penetrate to a maximum depth at the equator; i.e., reach a minimum altitude before it is absorbed. At points away from the equator towards either pole, the penetration decreases or the minimum altitude increases. A well defined meridional gradient of heat input into the stratosphere thus develops at the time of equinox. This, in turn, results in a decrease of temperature at any given constant altitude surface from the equator to the poles which would cause low pressure centers at each pole and westerly winds over the entire globe.

This very simple picture can be extended to other periods, when the subsolar point moves away from the equator and can qualitatively explain many of the gross features of the global circulation pattern⁷²⁻⁷⁶.

That this circulation pattern is also strongly dependent on the vertical distribution of ozone can be seen in the following summary form⁴²:

The important mechanisms for heating of the atmosphere below about 80km are the absorption of solar radiation by ozone and of infrared radiation by water vapor and carbon dioxide. Detailed calculations of the radiative budget of each layer between 50 and 70km show that there is a net gain of heat due to absorption at the bottom part of this layer and a loss at the top. This condition can only lead to a convective transport of heat to counteract the radiative unbalance. The magnitude of the convection at any time and location in the atmosphere will obviously depend strongly on the prevailing ozone distribution and on the solar zenith angle.

The above examples serve to emphasize the close interrelationship that exists between photochemical, radiative, and dynamical processes. Many authors have analyzed the role of ozone in the atmospheric heat budget by using assumed or "standard" distributions of ozone⁷¹⁻⁸⁶. Others have attempted to calculate ozone concentrations theoretically by using observed air densities and temperatures.

Leovy⁷² notes that not only does the temperature depend on the ozone distributions, but the converse is also true⁸⁷. He performed an iterative type of calculation which simultaneously took into account the photochemical and radiative aspects of the problem and which resulted in the simultaneous determination of ozone and temperature distributions. This analysis and many others⁷¹⁻⁸⁷ demonstrate that if the actual ozone distribution could be measured at a given time and location, the heat budget and temperature profile appropriate to that location could be computed. This information could in turn be incorporated into hydrodynamic models which relate atmospheric motion to the temperature field. Details of the analytical procedure for calculating the velocity field from a knowledge of the differential heating have been set forth by Lindzen and Goody⁸⁸, who took into account the various forms of couplings between ozone concentrations, temperatures, radiative and photochemical effects, and wind motions. This latter work and those of Davis⁸³ and Bekoryukov⁴⁷ in particular, show that given sufficient data concerning ozone distribution over large areas, analytical techniques can be used to deduce the atmospheric response, in terms of atmospheric circulations, to the non-uniform solar heat input.

2.3.3 DIRECT CORRELATIONS BETWEEN ATMOSPHERIC OZONE AND AIR CIRCULATIONS

In recent years, it has been possible to perform simultaneous measurements of ozone vertical distributions, temperatures, and atmospheric

wind velocities. Breiland⁸⁹ has examined the results obtained with the chemiluminescent ozone soundings during weekly balloon flights at a network of stations in North America. By direct correlation, it was established that significant changes in the temperature lapse rate or in the wind field frequency are associated with correspondingly significant changes the partial pressure of ozone. In particular, the stratified nature of the atmospheric wind field and thermal structure is reflected to a high degree in the ozone soundings.

Stickse⁹⁰ and Paetzold⁴⁹ have shown that there exists a relationship between ozone content and the position of the subtropical jet stream relative to the location of the observations. With few exceptions, the jet stream, a core of winds with speeds in excess of 50 knots, was found to the south of the ozonesonde station whenever double maxima were found in the vertical profile. Stickse, by taking in account several meteorological criteria, analyzed this relationship in terms of the atmospheric dynamics which are responsible for the double maxima.

More recently, Hering^{61,91} has demonstrated the value of broadscale ozone determinations in diagnostic studies of atmospheric circulation processes. By virtue of a network of 12 ozonesonde stations distributed over North America, ozone concentrations were systematically measured at the same time that data pertaining to pressure, temperature, and humidity were taken at the various stations. The results, as reported by Hering, leave no doubt that continuous observations of ozone concentrations taken simultaneously over several geographic locations could serve to assess the importance and correctness of the several proposed relationships between ozone and atmospheric circulation which have appeared in the literature.

The studies which have been cited in this section are being carefully analyzed in order to determine the optimum satellite orbits, the

range of latitudes and altitudes of ozone distribution measurements, etc., which would prove to be of the greatest value in diagnosing global scale air mass motion.

2.3.3.1 Correlations Between Ozone and Other Atmospheric Parameters

In the course of the study performed during this program effort, an impressive number of literature articles were found which describe observed correlations between atmospheric ozone content and various meteorological parameters. The main objective of this study was to demonstrate the value of monitoring the ozone distributions on a world-wide basis as a means of tracing large-scale atmospheric motions. The relationship of ozone to other meteorological properties was therefore not examined in detail. However, references to the articles which relate evidence for these correlations are included in Section 9.3.

The existence of these correlations suggest that ozone measurements may be of value not only for tracing winds, but also for providing indirect information concerning the values of other atmospheric parameters. That is, once the exact nature of the correlations are established, a remote ozone measurement may allow the values of other parameters to be inferred. An indication of how the total ozone content can be related, for example, to temperature at a given pressure level is seen in Figs. 2-7 and 2-8. These figures were taken from Godson's work²² in which the correlations at different latitudes were compared. Other investigators^{40,66,92,93} have discussed the relationship between temperature and total ozone amounts as a function of latitude and season, and in terms of horizontal advection and vertical motion. The relationship is a complex one but, as Figs. 2-7 and 2.8 and Godson's discussions indicate, it can be analyzed and understood on a semi-empirical basis.

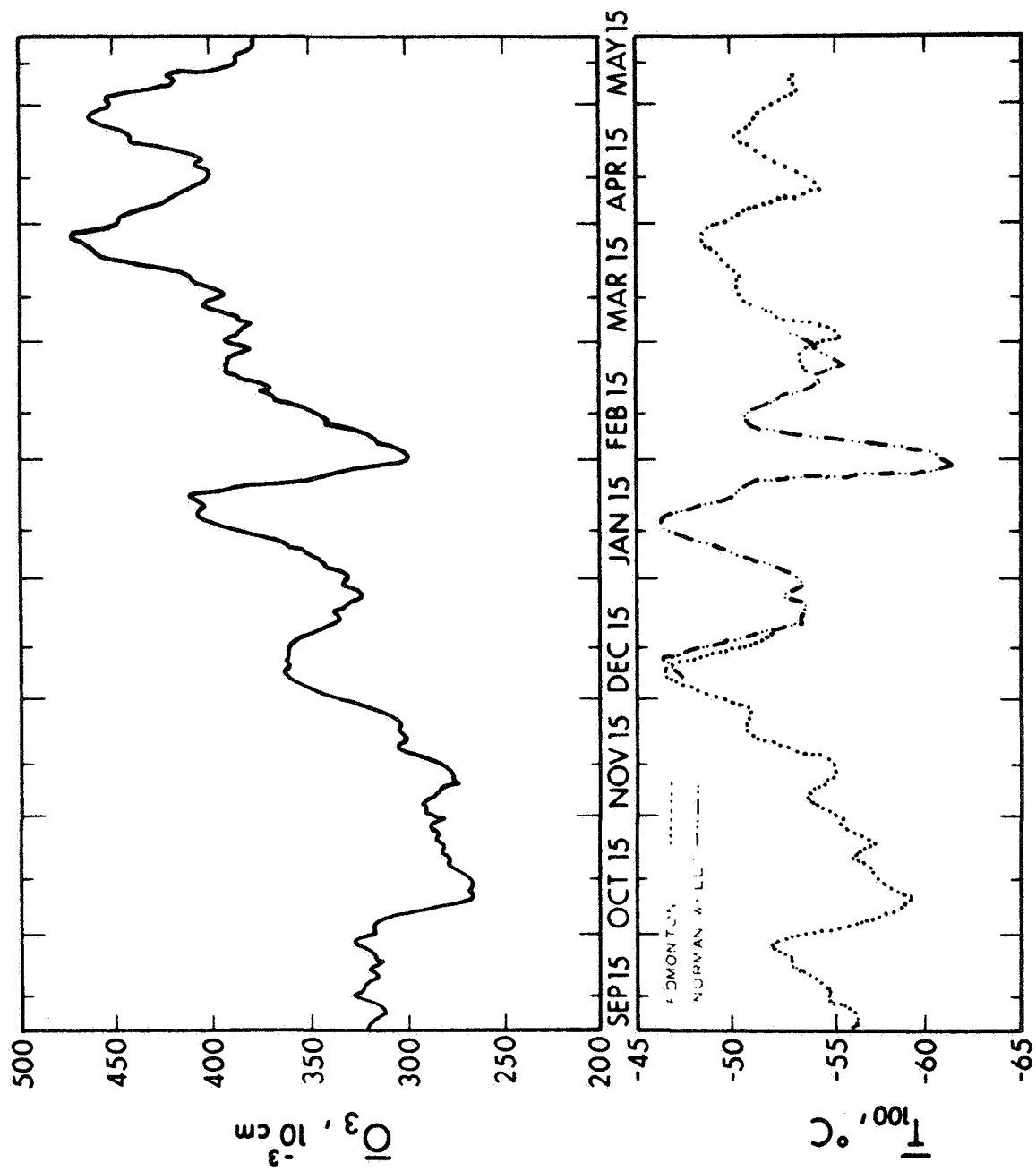


Figure 2-7. 10-Day Running Means of 100 mbar Temperature and of Total Ozone for 1953-54 Winter at Edmonton, Canada (Godson, 1960)

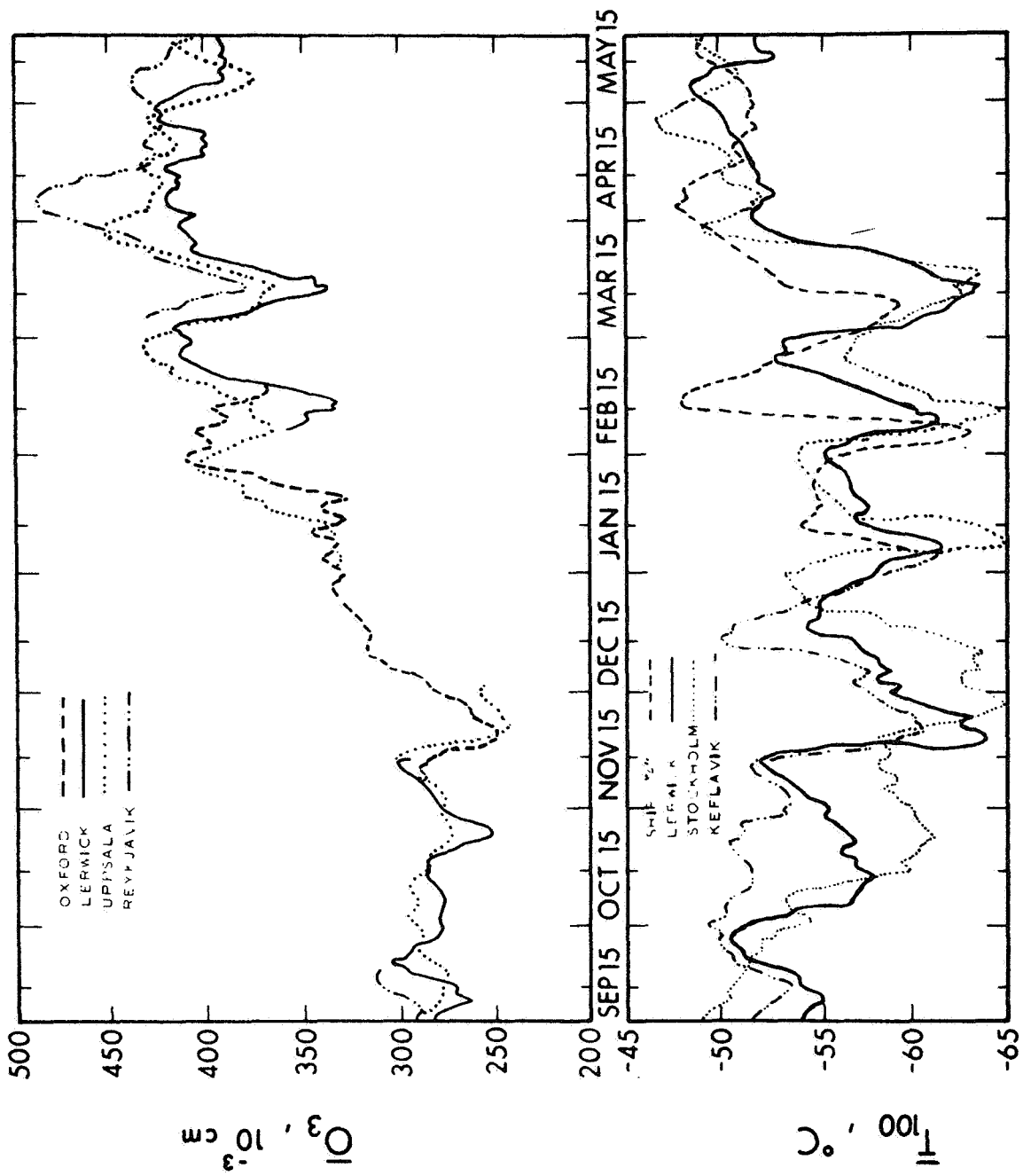


Figure 2-8. 10-Day Running Means of 100 mbar Ozone Temperature and of Total Ozone for 1953-54 Winter European Ozone Stations Near 60° N (Godson, 1960)

Correlations between ozone and other meteorological parameters are too numerous to discuss here; the titles of the articles referred to in Section 9, however, serve to illustrate the varied nature of the correlations which have been observed.

2.4 OZONE MONITORING AS A MEANS OF TRACING ATMOSPHERIC AIR MASS MOTIONS

The results of the many investigations cited above show that there is a dual connection between the distribution of atmospheric ozone and atmospheric circulations: (1) the atmospheric circulation effects a transfer of ozone from regions of high content to regions of low content, or vice-versa, and, together with photochemical processes, accounts for the observed distributions and their variations, and (2) absorption of solar radiation by non-uniform latitudinal, longitudinal, and vertical distributions of ozone provides one of the principal driving forces for the atmospheric circulation in the form of temperature gradients. The atmospheric circulation-ozone interrelationship has been extensively investigated by numerous workers, and the basic physical and meteorological principles involved are believed to be well understood. It is reasonable to assume that by incorporating empirical correlation data into circulation computations which are based on photochemical-radiative-hydrodynamical models, the role that ozone plays in meteorological processes will be understood in detail. The need at present is for increased observational data on the distribution of ozone, particularly on a continuous basis and on a global scale. It is evident that the study of atmospheric ozone has advanced to such a stage that, given such data, it can lead to a complete definition of the atmospheric circulation-ozone interrelationship.

SECTION 3

OZONE SPECTROSCOPY

Any optical technique that is to be developed for the quantitative measurement of ozone concentrations will depend on an accurate knowledge of the absorption properties of the ozone molecule. The certainty with which the absorption coefficients of ozone in the infrared, ultraviolet, and visible spectral regions are known will be one of the factors determining the accuracy of atmospheric ozone measurements. For this reason, an extensive search of the literature was conducted to compile all available material on the spectroscopic properties of ozone. This literature search resulted in a vast amount of information concerning the visible, UV, and IR absorption bands of ozone, as is indicated by the lengthy bibliography in Subsection 9.4.

A discussion of the absorption bands of ozone should also include a brief review of the chemical structure and vibrational and electronic energy levels of the molecule, since these properties strongly influence the changes in the band structure that accompany changes in temperature and pressure. These properties have recently been reviewed by G. Herzberg.⁹⁴ These factors will have a strong bearing on the interpretation of spectroscopic measurements in terms of absolute ozone concentrations. Conversely, by properly accounting for the effects of temperature and pressure it appears possible to extract, from the ozone measurement data, values of atmospheric pressure and temperature at the same altitudes for which ozone

concentrations are obtained. These possibilities were not examined in detail during this program effort, however, the main emphasis being placed on an evaluation of the reliability of the several sets of published values for ozone absorption coefficients. The objective of this present section is to fully describe the absorption spectrum of ozone for reference, as analyses of the measurement techniques are discussed in subsequent subsections of this report. As will be seen, a great wealth of information concerning ozone absorption has been obtained by numerous investigators, so that the values of the molecular quantities which are required in any optical measuring technique, i.e., absorption coefficients, can be considered to be known to a high degree of accuracy. Furthermore, the fact that they are known over a wide spectral range and under a variety of conditions promises great versatility for optical ozone measurement techniques.

3.1 CHEMICAL STRUCTURE AND VIBRATIONAL AND ELECTRONIC ENERGIES

Trambarulo et al,⁹⁵ and Robinson⁹⁶ have reviewed the chemical structure and energy levels of the ozone molecule and analyzed the electronic configuration in terms of valence-bond and molecular orbital theory. The best data indicates that the three atoms of oxygen in an ozone molecule form an isosceles triangle with an apex angle of $116^{\circ} 49\text{min.} \pm 30\text{min.}$ The two end oxygen atoms are connected to the central atom by chemical bonds which can be considered to be intermediate in character between single and double oxygen-oxygen bonds. The two equal bond lengths have been measured at $1.278\text{\AA}$ by both microwave⁹⁷ and electron diffraction⁹⁸ methods.

Figure 3-1 consists of a partial electronic energy diagram of the ozone molecule. The levels shown are labelled by standard spectroscopic notation, the assignments being made in accordance with

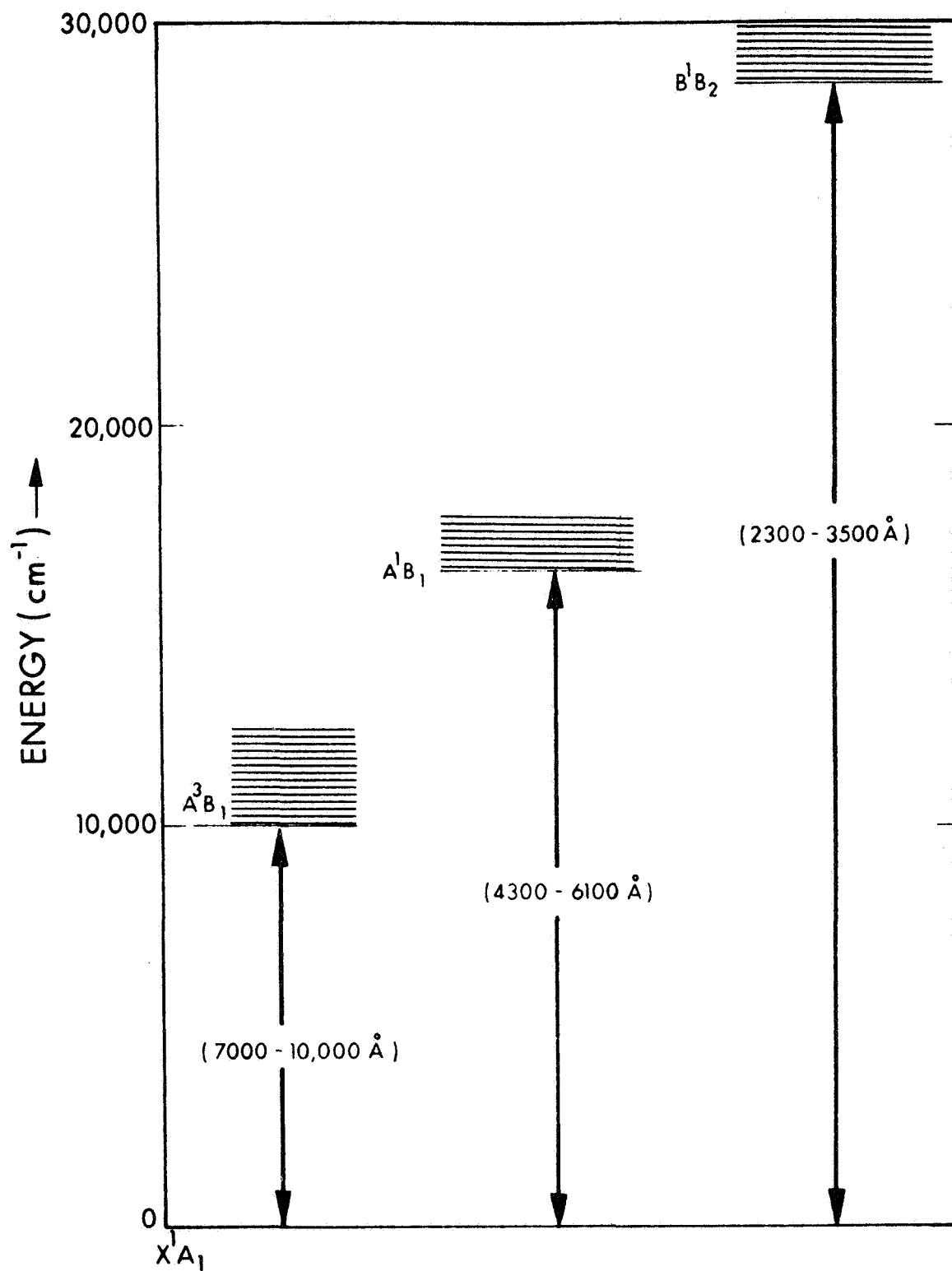


Figure 3-1. Electronic Energy Level Diagram for Ozone

theoretical predictions. It must be emphasized that the assignments are tentative and that little is known concerning the nature of the excited electronic states, A^3B_1 , A^1B_1 , and B^1B_2 .

The electronic transitions from the ground state, X^1A_1 , to the B^1B_2 state give rise to the wide absorption bands (Hartley-Huggins bands) that appear in the region between 2300Å and 3500Å and which account for the atmospheric solar cutoff. The diffuseness of the absorption band is due partly to the unresolved vibrational and rotational structure of the band, but mostly to the inherent diffuseness of the B^1B_2 state. Similarly, the Chappius bands at 4300 to 6100Å and the near-infrared bands between 7000 to 10,000Å are diffuse due to the inherent widths of the A^1B_1 and A^3B_1 states, respectively. This diffuseness corresponds to a predissociation of the ozone molecule. That is, following the act of absorption of radiation there is a large probability that the ozone molecule will instantaneously undergo a radiationless transition into a dissociative state which consists of an oxygen molecule and an oxygen atom. Thus, the absorption of ultraviolet, visible, and near-IR radiation results, at least to a high degree, in the decomposition of the ozone molecule. The significance of this, from the point of view of ozone measurements, is that the ozone molecule does not reemit the same radiation that it absorbs. There is no evidence in the literature for a fluorescence band between 2300Å and 3500Å which corresponds to the inverse transition, $B^1B_2 \rightarrow X^1A_1$, of the Hartley-Huggins bands. Nor has any fluorescence been reported in the vicinity of the Chappius or near-IR absorption bands. All ozone detection and measuring schemes which depend on a fluorescence-type backscattering phenomena are, therefore, excluded from consideration, with the possible exception of the IR transition at 9.6μ.

The best available data indicate that two of the fundamental vibrational frequencies of ozone are at 710 cm^{-1} and 1043 cm^{-1} .

These assignments are consistent with the infrared (vibrational) data, and also with the observed temperature dependence of the vibrational structure in the ultraviolet (electronic) absorption bands. These values could conceivably be used to advantage in the measurement of upper atmospheric temperatures concurrently with the ozone measurements.

That is, if the band structure in the atmospheric ultraviolet absorption bands could be analyzed in terms of its temperature dependence, it would provide a measure of the temperature at the ozone altitudes. While this is an interesting possibility that should be kept in mind in future analyses, the present conclusion is that the complex structure of the UV bands has not yet been unambiguously interpreted in terms of individual vibrational transitions.

3.2 ABSORPTION SPECTRA OF OZONE

The absorption spectra of ozone in the visible, ultraviolet, and infrared spectral regions have been measured by literally dozens of workers.⁹⁹⁻¹⁵² The absorption bands of interest are illustrated and discussed in this section.

3.2.1 VISIBLE ABSORPTION BANDS

Figure 3-2 shows the wavelength variation of the absorption cross section of ozone in the region of the visible Chappius bands⁹⁹ as measured by Vigroux.¹⁰⁰ It is noted that there is a strong wavelength dependence of both the ozone cross section and the scattering cross sections of air molecules in this spectral region. This allows the contribution of the air molecules to the total attenuation of solar radiation to be accounted for, and also permits the measurement of ozone concentrations to be made from the measurement of

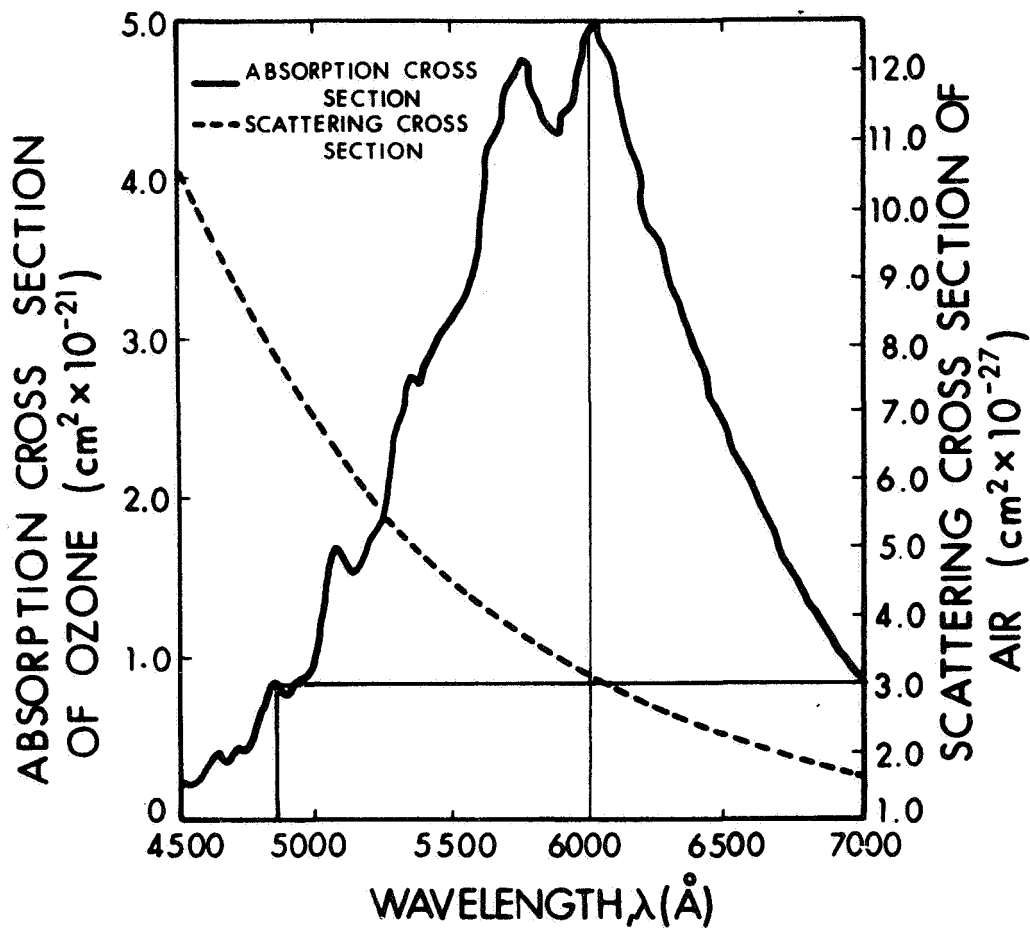


Figure 3-2. Absorption Cross Sections of Ozone and Scattering Cross Sections of Air (cm^2 per molecule) in the Region of the Chappius Bands

relative intensities of transmitted solar radiation at a pair of wavelengths. These points will be elaborated upon in Section 6. The absorption represented by the Chappius band cross section is relatively weak. However, through a path length which traverses the total atmosphere there occurs sufficient attenuation in these bands to measure ozone concentrations. The Chappius bands will prove to be instrumental in the evaluation of some of the active and passive techniques discussed in this report.

3.2.2 ULTRAVIOLET ABSORPTION BANDS

The ultraviolet absorption bands of ozone between $2300\text{\AA}$ and $3500\text{\AA}$, are responsible for the atmospheric cutoff of UV solar radiation. In this spectral region, the absorption of solar radiation is extremely strong, and extremely small quantities of ozone could be detected by utilizing these bands. This will prove to be of value in extremely high altitude measurements (35 to 80 km). Three of the absorption curves in the ozone Hartley-Huggins bands, as determined by different authors, are reproduced as the top part of Fig. 3-3. The values of the absorption coefficients are seen to drop off rapidly towards wavelengths longer than those shown in the figure and there is considerably more structure in the bands. This structure is associated with vibrational and rotational transitions of the molecule and is temperature-dependent. It is this portion of the bands which could possibly be utilized in the measurement of temperatures of the upper atmosphere. It is seen that at certain wavelengths the determinations differ by as much as 25%. The values measured by Vigroux¹⁰⁰ have generally been considered to be the most reliable and were adopted by the International Ozone Commission in 1957 for calculation of the amount of atmospheric ozone from measurements by Dobson spectrophotometers. Inn and Tanaka¹⁰⁷ have also endorsed Vigroux's values as representing the most reliable set of ozone absorption coefficients in the $2000\text{-}3000\text{\AA}$

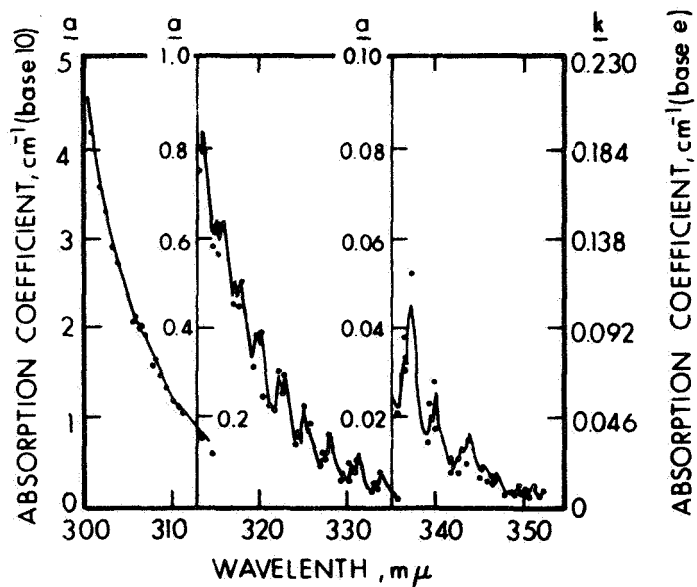
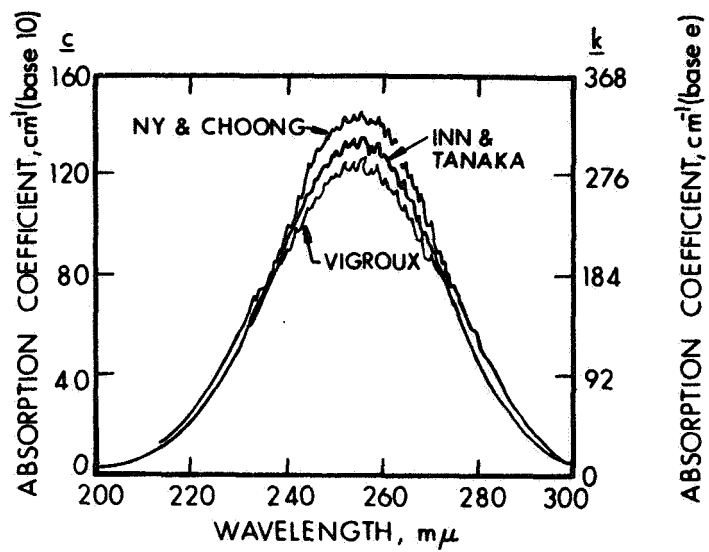


Figure 3-3. The Ultraviolet Ozone Absorption Profiles as Determined by Three Sets of Authors (top). Absorption Coefficients on the Long Wavelength Edge of the Ultraviolet Bands, as Determined by Vigroux

region. On the other hand, Dobson¹⁰³ and Hamilton and Walker¹⁰⁴ have claimed that Vigroux's measurements are considerably in error and have independently measured ozone absorption coefficients for use in their calculations. In spite of this, Vigroux's values will be used hereafter in this program for two reasons: (1) Vigroux has performed the only detailed set of measurements which yield the temperature dependence of the ozone coefficients; thus, the ozone absorption coefficients which should be used in measuring atmospheric ozone (-40° to -50°C) have been derived¹⁰⁵ from the temperature-dependence data given by Vigroux, and (2) the wavelengths used in the Dobson spectrophotometer technique are in the region between 3055 and 3398Å. This region is characterized by a complex vibrational structure (see Fig. 3-3, lower curve) which has not been completely analyzed, and which would understandably cause difficulty due to the temperature dependence of the absorption profile. The absorption band at wavelengths shorter than 3055Å is truly diffuse and its profile would not exhibit strong fluctuations with changes in temperature. In the passive technique being recommended in this report, measurements in the 3055-3400Å region will also be required in addition to measurements in the diffuse portion of the band (see Section 6).

The temperature dependence will be taken into account by using the aforementioned values of the coefficients which correspond to the low atmospheric temperatures and/or by selecting wavelengths within the band structure for which there is little or no temperature dependence.¹⁰⁶ The order of magnitude as well as the reliability of the absorption coefficient values have been the primary considerations in the choice of wavelength to be used in the proposed optical techniques for ozone measurement. This will be seen in the discussions in Section 6.

3.2.3 INFRARED ABSORPTION COEFFICIENTS

Figure 3-4 is reproduced from a publication by J. Strong¹⁰⁷ who has suggested that this band be used to measure atmospheric pressure simultaneously with ozone content (see subsection 5.1.3). The band is associated with the 1043 cm^{-1} fundamental vibration and, as is seen in the figure, it occurs in a region that is relatively free of absorption by other atmospheric constituents.

As a result of the detailed experimental measurements and the theoretical calculations by Clough and Kneizys¹⁰⁸, the 9.6 micron absorption band can be considered to be completely analyzed. A complete vibrational-rotational analysis, which includes the effect of Coriolis coupling and a second-order distortion interaction, has allowed the contribution that each vibrational transition (ν_1 and ν_3) makes to the 9.6 micron absorption band to be evaluated as a function of wavelength. Figure 3-5 shows this band in greater detail. The portion of the spectrum appearing in the figure shows the agreement obtained between measured and computed values. Since the integrated absorption of the band has been previously calculated by Walshaw¹⁰⁹, the intensities in both bands (ν_1 and ν_3) can be expressed in absolute units. Thus, a set of reliable absorption coefficients is available for use in any optical technique utilizing the 9.6 micron absorption band, whether it involves discrete line absorption or integrated absorption.

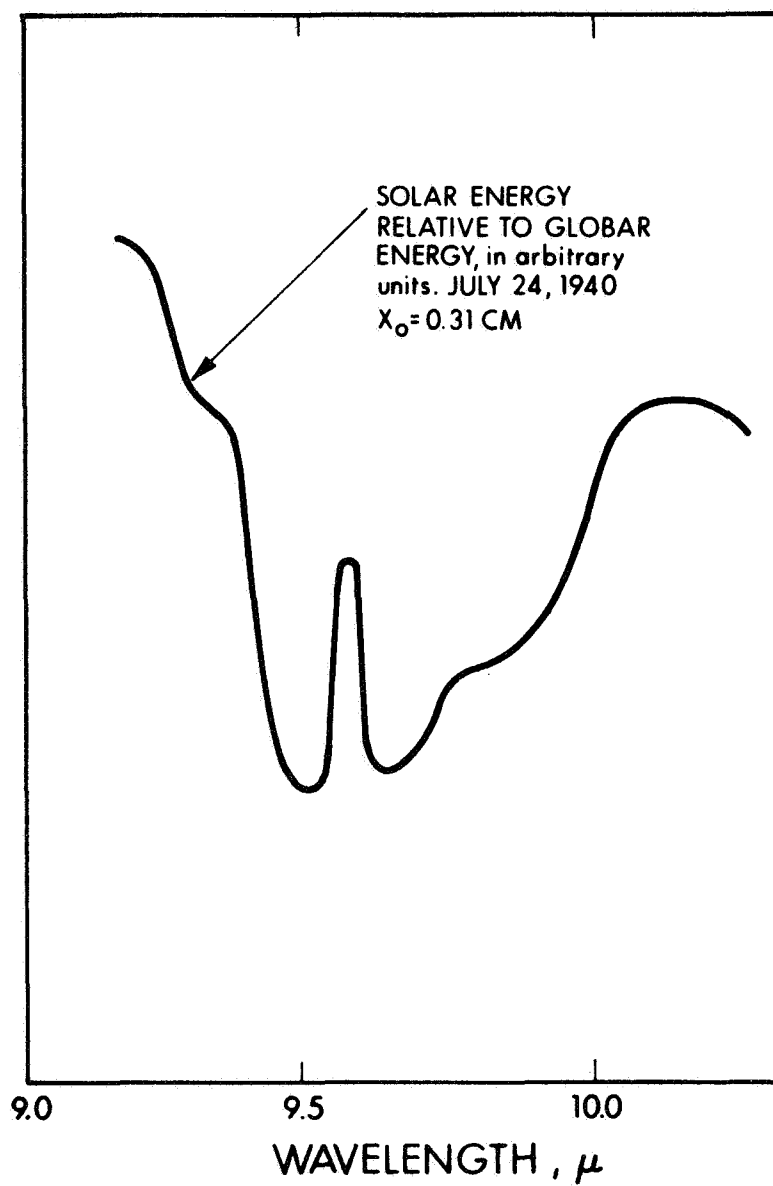


Figure 3-4. 9.6 μ Absorption Band of Ozone

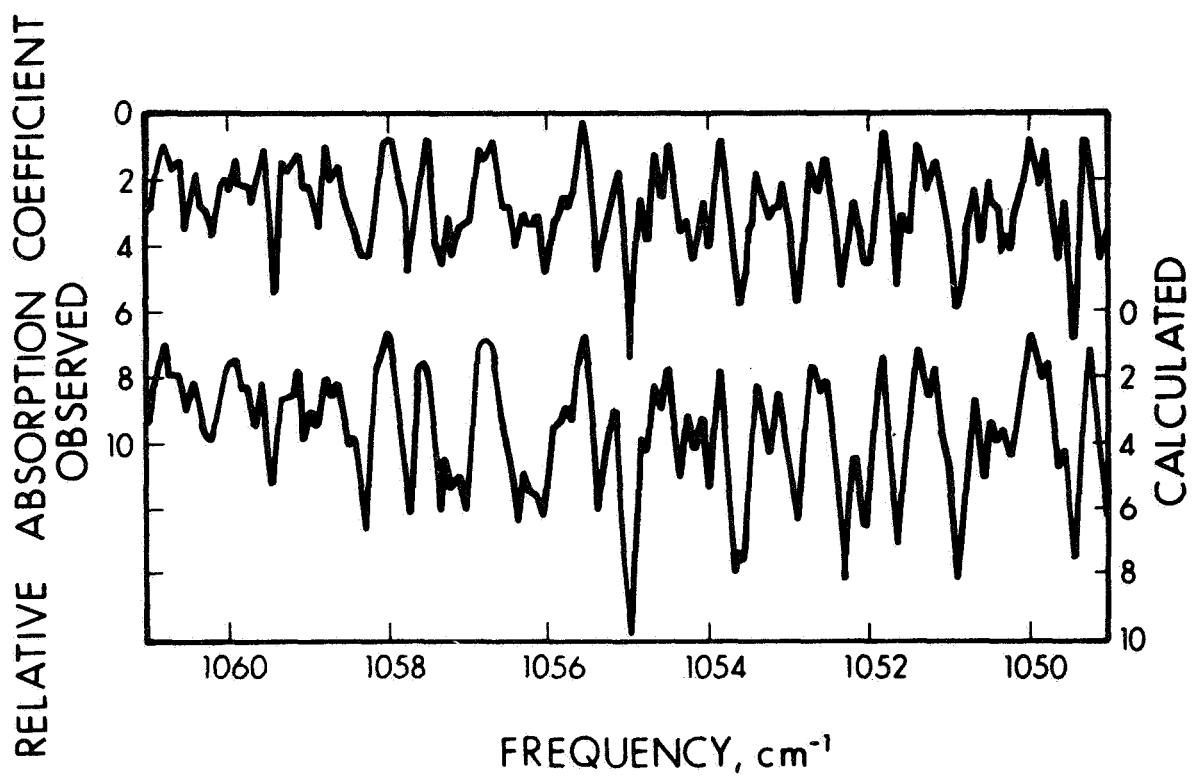


Figure 3-5. A Portion of the 9.6 μ Ozone Absorption Band as Measured Under High Resolution (upper curve) and as Reconstructed by Computer Analysis (lower curve)

SECTION 4

METHODS OF ATMOSPHERIC OZONE MEASUREMENTS (NON-SATELLITE TECHNIQUES)

Since the ozone layer was discovered¹³⁸ in 1913, a great variety of optical techniques have been employed to measure both the total ozone content and its vertical distribution. The total content can be determined from the ground rather easily by using the sun as a source for the absorption measurements. The vertical distribution can likewise be measured from the ground by means of the so-called "Umkehr" effect,¹⁵³⁻¹⁵⁶ but this method suffers due to poor accuracy. Paetzold¹⁵⁷⁻¹⁶³ performed a number of measurements by the method of using eclipses of the moon, but measurements can be made by this technique only when the moon is in a favorable position with respect to the sun and an observer on the earth. More recent techniques which have been used include the method of balloon ascents, airplane and V-2 rocket spectroscopy, and satellite reflection spectrometry. These methods are all limited in scope since they allow measurements over only limited ranges of altitudes. Furthermore, in common with most techniques which have been used, these methods can be used only over a limited number of geographic locations at any given time.

In addition to the optical methods, various chemical methods have been developed which yield excellent data concerning vertical ozone distribution above individual ground stations. Subsection 9.5 of this report consists of a list of references to articles which deal with methods of measuring the total atmospheric ozone

content as well as its vertical distribution. These methods range from such early methods as the method employing lunar eclipses to the more recent techniques involving satellites, rockets, balloons and airplanes.

Details of these techniques will not be discussed here, an excellent review having been presented recently by Craig³. It suffices at this point to note that an impressive number of detailed descriptions of optical ozone measuring techniques appear in the referenced articles, from which valuable information can be drawn.

For example, the Götz or Umkehr technique is of interest not because of its accuracy, which is, in fact, poor as it pertains to vertical distribution determinations, but because it has been exhaustively refined by Dobson and other workers. In the process of improving the technique, many factors, such as ozone absorption coefficients, wavelengths to be monitored, slit widths and design of the measuring spectrophotometer, etc., were carefully analyzed by these workers. Since these factors also must be considered in the present program, advantageous use can be made of the knowledge that has been gathered as a result of the above previous efforts. Therefore, the Götz technique, as well as other techniques that are represented in the list of references in Subsection 9.5, will continue to be analyzed in order to help evaluate critical parameters that need to be specified in the techniques under investigation in this program.

A chemical technique of particular interest is the chemiluminescent method developed by Regener.¹⁶⁴ This technique makes use of the chemiluminescent reaction of ozone with a disc sensor coated with silica gel and an organic dye, Rhodamin B. The ozone concentration is determined by measuring the light energy released by the reaction.

Due to the extremely rapid response of the device to changes in ozone concentration, very high resolution measurements are made by this technique. The ozonesonde and the conventional radiosonde are flown together in sounding balloons and the ozone signal is telemetered to a ground receiver along with data on temperature, pressure, and humidity. It is with this technique that Hering and co-workers obtained the data at the 12 ozonesonde stations, as discussed in Subsection 2.3.3.3 of this report. This technique is of interest since it is probably the most reliable and well developed technique for taking ozone measurements over a single ground station. Since it is independent of optical techniques, it would appear to be the ideal supplementary technique which could be used as a crosscheck to the advanced concepts which are being evaluated in the current program. That is, once an orbiting satellite is making ozone measurements, ozonesonde balloons could be used at isolated geographical locations for independent measurements of vertical ozone distributions. The results of the two methods could then be directly compared. A system of ozonesonde stations that could compile as much data as a single orbiting satellite would, of course, be highly impractical, if not impossible, to establish.

SECTION 5

ADVANCED CONCEPTUAL METHODS OF OZONE MEASUREMENTS FROM ORBITING SATELLITES

The literature search performed during this program effort has turned up an impressive amount of information relating to the use of optical techniques in the measurement of atmospheric ozone content. A variety of techniques which apply to the measurement of both the total ozone content and its vertical distribution have been critically examined and evaluated.

This survey has shown that there are a number of optical techniques for ozone measurement which could be used in conjunction with an orbiting satellite. These would be essentially independent and supplementary techniques, and it may prove desirable to instrument one satellite to perform the measurements by two or three of these techniques simultaneously.

The techniques which have been considered can be classified as being either passive or active methods. The former involve measurements made of the radiation emitted by a natural source, such as the sun, or by the atmospheric ozone itself. The latter rely on the use of radiation provided by a man-made source, such as a laser, which may either be a ground-based or satellite-borne instrument. The following paragraphs describe briefly the optical ozone-measuring methods which merit consideration for a satellite application.

5.1 PASSIVE TECHNIQUES

The two passive techniques that are seriously being considered for recommendation are (1) the determination of vertical ozone content by a measurement of the differential attenuation of solar radiation which traverses the earth's atmosphere, and (2) the determination of vertical ozone content by analysis and the infrared radiation emitted by the atmospheric ozone. The theoretical principles for both of these techniques have been well developed and a limited amount of observational data has been acquired which confirms the essential correctness of both methods.

5.1.1 DIFFERENTIAL ATTENUATION OF SOLAR RADIATION

This technique depends on viewing the solar rays after they pass tangentially through the earth's atmosphere. The satellite-borne detector monitors the intensities at a number of wavelengths for different geometrical ray paths and the vertical distribution can be deduced from straightforward physical and geometrical considerations. This method involves the use of visible and near ultraviolet radiation, as is described in detail in Section 6.

5.1.2 INFRARED EMISSION BY ATMOSPHERIC OZONE

This technique utilizes infrared radiation which is emitted by the ozone molecule and is analogous to a method which has been used to deduce vertical resolution from ground-based measurements.^{45,165,166,167}

5.2 ACTIVE TECHNIQUES WITH OPTICAL PROBES

The use of active probes represents a new concept in ozone measurements principally because such probes have become feasible only since the development of the laser and since it has become possible to

consider the use of a satellite as a transmitting or receiving station. A program of measurements incorporating active probes would offer many advantages including the fact that it would not depend on the position of the sun with respect to the satellite position. It would also be capable of operation during either day or night, thus providing valuable information concerning diurnal variations of the vertical ozone distribution. Such information would be of value in clarifying the role of ozone in atmospheric processes, including horizontal and vertical air transport mechanisms. An active probe technique would be expected to provide at least as much information concerning the vertical distribution of ozone as any of the passive techniques under investigation.

The methods discussed here depend on the availability of high-power laser radiation at wavelengths which can be utilized in the determination of atmospheric ozone. At present, the class of laser most likely to fulfill this need is the so-called Raman laser. This name is derived from the fact that laser-like radiation, i.e., highly intense, pulsed, coherent, monochromatic, and directional radiation, can be produced at a variety of wavelengths by the phenomenon known as stimulated Raman scattering. The production of Raman lasers requires the use of a high intensity, pulsed primary laser such as the ruby or neodymium laser (6943μ and 1.06μ , respectively) or the use of second harmonic laser radiation at $3471\text{\AA}$ or $5300\text{\AA}$, respectively.

5.2.1 SATELLITE-BORNE RAMAN LASERS, SATELLITE-BORNE DETECTORS

A Raman laser aboard a spacecraft could be used to provide a source for ozone measurement by absorption techniques. As such, the laser radiation would be a substitute for solar radiation in the first passive technique discussed above if used in a two-satellite configuration. Much more versatility would result by using a laser source,

however, since such a technique would not suffer from geometrical restriction inherent in using solar radiation. The laser source could also be used in a single satellite configuration to measure the ozone content by the well known technique based on back scattering of UV radiation by air molecules.¹⁶⁸⁻¹⁷¹

5.2.2 GROUND-BASED RAMAN LASERS, SATELLITE-BORNE DETECTORS

This technique essentially reverses the role of emission source and detector in the ground-based method which determines total ozone content by measuring the attenuation of solar radiation at different incident zenith angles. The use of a laser source again eliminates geometrical limitations which are imposed when the sun is used as a source for absorption measurements.

5.3 SELECTION OF SATELLITE METHODS FOR OZONE MEASUREMENTS

As a result of the survey and preliminary evaluation of optical techniques performed during the first year of this program, two optical techniques have been chosen for detailed analysis. Although others may be seriously considered in later phases of the program, it has been decided to concentrate for the present on one active and one passive technique which both appear to be well within the state of the art. The two techniques are complementary with respect to the type of information they yield. The principal on-board instrumentation requirements for both techniques would be spectral filtering devices and photomultiplier detectors. It is felt that the two types of measurements would be compatible from the point of view of instrumentation on a single satellite, and would allow the atmospheric ozone content to be measured with both high horizontal and vertical resolution.

Progress has been made in demonstrating the feasibility of both of these techniques. This progress is reviewed in Sections 6 and 7 of this report.

SECTION 6

OZONE DETERMINATION BY THE METHOD OF DIFFERENTIAL ATTENUATION OF SOLAR RADIATION

With the development of instrumented satellites, exploratory measurements of ozone profiles over a number of locations have been made^{172,173} by the method referred to herein as the differential attenuation of solar radiation. However, the spectral and spatial resolutions which characterize these measurements do not begin to approach the ultimate in the state-of-the-art for satellite-borne instrumentation. The discussions appearing in this section are intended to illustrate the extent to which this method can be improved upon by refining the measurement and data reduction aspects in a satellite application.

The underlying principles of this technique were also used by Venkateswaran, et al¹⁷⁴, to determine the vertical distribution of ozone with the aid of the Echo communications satellite, 1960 Iota I. However, whereas these investigators performed ground-based measurements of solar radiation reflected by the satellite, the technique described here would involve direct measurements of the solar radiation by an instrument aboard a satellite. Several advantages result from the ability to make direct measurements, including increased sensitivity, resolution, and accuracy. Furthermore, depending on the type of orbit, measurements can be made over a selected number of locations around the world on a quasi-continuous basis.

Certain features of the problem, such as the need to correct for the refraction of solar rays by the earth's atmosphere, and the de-

parture of the sun's surface from a point source, while discussed here, will not be treated fully until the subsequent year's effort. The emphasis in the discussion below will be on demonstrating the feasibility and efficiency of the method.

6.1 OPTICAL PRINCIPLES OF THE DIFFERENTIAL ATTENUATION TECHNIQUE

The principles involved can be illustrated by reference to Fig. 6-1. Measurements of solar radiation intensities are taken when the sun's rays are passing tangentially through the earth's atmosphere and the instantaneous position of the satellite is at S_1 (during orbital sunrise or sunset). For purposes of illustration, a satellite altitude of 1000 km is shown in the figure, but the technique is valid for a wide range of altitudes. The atmosphere, which is considerably exaggerated in the figure, is divided into a number of shells above the sunset or sunrise point, S_u , and below a height h_1 . In the example shown, a model with ten shells, each of 10 km thickness, has been adopted. In principle, any number of shells can be assumed, although a practical limitation will be imposed by the rate at which the satellite-borne instrument can make measurements at the wavelength bands of interest. It can be seen from the discussion below that the greater the number of measurements per sequence, the greater the accuracy with which the vertical distribution can be defined. In the calculations presented later in this section, the model adopted contains 80 spherical shells each of 1 km thickness. Preliminary orbital, detector, and optical analyses indicate that this does not represent an unrealistic rate of measurement taking. The first shell (highest altitude) is bounded by the altitudes h_1 and h_2 (which in the example of Fig. 6-1 take the values of 100 and 90 km, respectively). Similarly, the i th shell is bounded by the altitudes, h_i and h_{i+1} . The satellite can selectively view a ray which, at the local sunset point S_u , passes only through the i th shell. This ray is referred to as R_i and the distance that it traverses in the i th layer is denoted

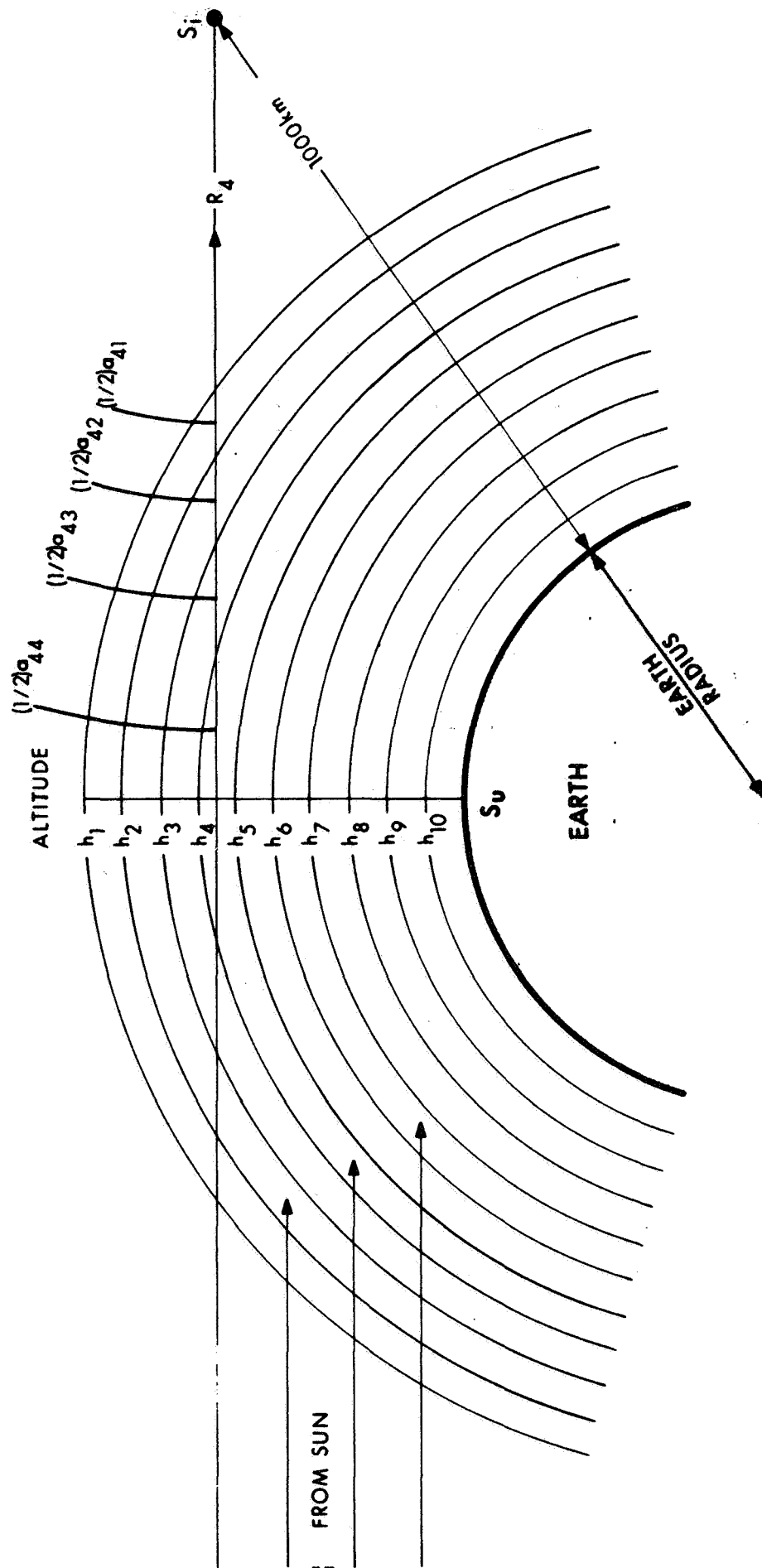


Figure 6-1. Geometry Involved in Direct Measurement of Attenuated UV Solar Radiation

by a_{ii} . However, in passing through the entire atmosphere any ray, other than R_1 , will traverse a certain distance, a_{ij} , through the j th layer where $j = 1, 2, \dots, i-1$. The values of a_{ii} and a_{ij} can be determined by geometrical considerations.

The degree of attenuation of any solar ray passing through a tangential path in the atmosphere will depend upon the wavelength and upon the number of absorbing and scattering molecules encountered. The assumption is made that the only significant absorption in the visible and near UV spectral regions is due to molecular ozone, an assumption that is certainly well justified. The Rayleigh scattering can be easily accounted for. The wavelength dependence is, of course, due to the variation with wavelength of the absorption coefficient, or cross section per molecule, of ozone, and the Rayleigh scattering cross-section of air molecules. The number of ozone and air molecules encountered by any tangential solar ray can, for purposes of illustration, be estimated from some adopted model of vertical atmospheric ozone distribution. This has been done for the calculations described in Section 6.2. The motion of the satellite serves as a scanning motion by means of which the attenuation through different atmospheric thicknesses is determined for each wavelength being monitored. The absolute intensities of the solar rays can be determined by direct measurement from a position in which the earth's atmosphere does not intervene. A measure of the differential attenuation is thus obtained for different paths through the earth's atmosphere. Data taken in this manner can be inverted by straightforward computer techniques to yield a vertical profile of the ozone and air distributions.

6.2 DETERMINATION OF MOLECULAR THICKNESSES

As mentioned above, the satellite is allowed to view the solar radiation which passes tangentially through the earth's atmosphere. The

finite size of the sun(which means that it cannot be considered as a point source) and atmospheric refraction are complications which will be discussed in subsequent subsection. For the present, it can be assumed that at any instant, in this portion of its orbit, the satellite views a single ray which passes without refraction at some uniquely defined altitude above the sunset point, S_u . This altitude, which can be determined from a knowledge of the orbital parameters, is denoted by h_{ii} . (The altitude above S_u at which the i th ray passes through the center of the i th atmospheric shell.)

The absolute intensity of the solar radiation, as measured by a satellite-borne detector, will depend on (a) the intensity of solar radiation in the wavelength band being monitored, and (b) the total optical thickness of the earth's atmosphere for the i th ray at the wavelength being monitored. The total optical thickness, τ , is defined here as the exponential factor relating the intensity, $I(\lambda)$, transmitted by the earth's atmosphere to the incident intensity, $I_o(\lambda)$, i.e.,

$$I_i(\lambda_j) = I_o(\lambda_j)e^{-\tau_i} \quad (6-1)$$

In equation (6-1) the subscript i is used to emphasize the fact that the optical thickness, and therefore the transmitted intensity, will depend on the particular ray path through the atmosphere; the subscript j is used to indicate that more than one wavelength will be monitored, for reasons to be discussed below.

The optical thickness for any ray of a given wavelength will be determined by the total number of attenuating molecules in the ray's path through the atmosphere. In the wavelength regions which will be used, the only important attenuation mechanisms are Rayleigh scattering by air molecules (N_2 and O_2) and molecular absorption by ozone. For

a given length traversed by a ray at a known altitude, the optical thickness will depend on the prevailing vertical distribution of these attenuating particles. The latter is known to be a variable property of the atmosphere, especially in the case of ozone. The following model vertical distributions of ozone and air therefore, have been adopted for this calculation. The ozone model adopted was the so-called average distribution given by the USAF Handbook of Geophysics, Ch. 8 (1961); the air distribution was taken from the work of Minzner, et. al. (AFCRC-TR-59-267, 1959.) For practical reasons, the earth's atmosphere is considered to consist of 80 concentric shells of one kilometer thickness each (instead of the ten shells shown in Fig. 6-1), and the air and ozone concentrations are assumed to be uniform within each shell. It is also assumed that the satellite can view a ray which passes through the center of each shell above the sunset point, a total of 80 such rays being monitored. (Ray number one is that ray which passes through the outermost, or first, shell at an altitude of 79.5 km above S_u , and the remaining rays and shells are numbered in increasing sequence as the altitude at which each ray passes above the sunset point decreases.) The distance that any ray traverses in each individual shell can be determined through simple geometry. These traversal lengths, a_{ij} , were determined with the aid of a computer program. This program, which will be referred to herein simply as OZONE, is completely flexible with respect to the number of shells and the vertical distribution of particles that can be incorporated into the computation. By weighting each length first by the ozone concentration and then by the air density appropriate to that altitude, the ozone and air thicknesses of each traverse length were determined. The total number of ozone and air molecules encountered by any ray in traversing the entire atmosphere is then simply obtained by summing all of the weighted traverse lengths for that ray.

The results of these computations are summarized in Table 6-1. The first two columns define the ray and sunset point altitude, while the third lists the local values of the air densities which were used. The total number of air and ozone molecules that would be encountered by each ray, with the assumed distributions, are listed in the last two columns. (In these latter columns the letter E denotes the exponent or power of the number 10.)

In the following subsection, a review is given of the manner in which the total molecular thicknesses for each ray are obtained from solar radiation attenuation measurements. Once the molecular thickness for each ray is known, the vertical profile can be computed with the aid of a program which is essentially the inverse of the OZONE program referred to above. This inverse program, or INVOZONE, has been satisfactorily prepared and used in sample computations. It will be modified for future analyses in order to determine the accuracy with which this passive measurement method can reproduce a variety of ozone profiles. This will be done by introducing uncertainties into the total molecular thickness values which reflect errors inherent in the intensity measurements and uncertainties in the ozone cross-section values.

6.3 OPTICAL THICKNESS DETERMINATIONS AND SELECTION OF WAVELENGTHS

Since both the Rayleigh scattering cross-sections for air molecules and the absorption cross-section for ozone vary with wavelength, a given molecular thickness represents a range of optical thicknesses. In this subsection results of optical thickness calculations will be presented. In addition, the manner in which these results help define the wavelengths that should be monitored will be discussed.

The measured quantity, from which the optical thickness of the atmosphere for a given ray is deduced, is the intensity ratio $I_1(\lambda_j)/I_0(\lambda_j)$.

TABLE 6-1

TOTAL MOLECULAR THICKNESSES FOR RAYS 1 - 80

Ray(i)	Altitude h_{ii} (km)	air($\frac{\text{Molecules}}{\text{cm}^3}$)		Molecular Thickness (Entire Ray)			
				Air		Ozone	
1	79.50	4.811	E14	7.7281	E21	2.803	E15
2	78.50	5.703	E14	1.4818	E22	3.480	E15
3	77.50	6.733	E14	2.1415	E22	4.341	E15
4	76.50	7.916	E14	2.8413	E22	5.432	E15
5	75.50	9.275	E14	3.6142	E22	6.814	E15
6	74.50	1.082	E15	4.4808	E22	8.551	E15
7	73.50	1.259	E15	5.4614	E22	1.073	E16
8	72.50	1.459	E15	6.5724	E22	1.347	E16
9	71.50	1.686	E15	7.8333	E22	1.693	E16
10	70.50	1.942	E15	9.2629	E22	2.129	E16
11	69.50	2.230	E15	1.0882	E23	2.678	E16
12	68.50	2.554	E15	1.2713	E23	3.368	E16
13	67.50	2.917	E15	1.4781	E23	4.238	E16
14	66.50	3.324	E15	1.7097	E23	5.334	E16
15	65.50	3.777	E15	1.9724	E23	6.722	E16
16	64.50	4.282	E15	2.2672	E23	8.462	E16
17	63.50	4.843	E15	2.5973	E23	1.064	E17
18	62.50	5.466	E15	2.9665	E23	1.338	E17
19	61.50	6.156	E15	3.3787	E23	1.688	E17
20	60.50	6.918	E15	3.8380	E23	2.120	E17
21	59.50	7.760	E15	4.3491	E23	2.669	E17
22	58.50	8.687	E15	4.9166	E23	3.330	E17
23	57.50	9.706	E15	5.5457	E23	4.135	E18

TABLE 6-1

TOTAL MOLECULAR THICKNESSES FOR RAYS 1 - 80 (contd)

Ray(i)	Altitude h _{ii} (km)	n _{air} ($\frac{\text{Molecules}}{\text{cm}^3}$)		Molecular Thickness (Entire Ray)			
				Air		Ozone	
24	56.50	1.083	E16	6.2426	E23	5.129	E18
25	55.50	1.205	E16	7.0113	E23	6.280	E18
26	54.50	1.340	E16	7.8606	E23	7.717	E18
27	53.50	1.487	E16	8.7962	E23	9.494	E18
28	52.50	1.673	E16	9.8661	E23	1.168	E18
29	51.50	1.884	E16	1.1084	E24	1.438	E18
30	50.50	2.122	E16	1.2463	E24	1.769	E18
31	49.50	2.388	E16	1.4016	E24	2.176	E18
32	48.50	2.694	E16	1.5777	E24	2.678	E18
33	47.50	3.028	E16	1.7751	E24	3.294	E18
34	46.50	3.447	E16	2.0036	E24	4.053	E18
35	45.50	3.933	E16	2.2677	E24	4.984	E18
36	44.50	4.482	E16	2.5702	E24	6.132	E18
37	43.50	5.140	E16	2.9212	E24	7.549	E18
38	42.50	5.886	E16	3.3251	E24	9.288	E18
39	41.50	6.750	E16	3.7903	E24	1.142	E19
40	40.50	7.758	E16	4.3283	E24	1.405	E19
41	39.50	8.936	E16	4.9519	E24	1.728	E19
42	38.50	1.030	E17	5.6741	E24	2.145	E19
43	37.50	1.190	E17	6.5131	E24	2.674	E19
44	36.50	1.375	E17	7.4861	E24	3.343	E19
45	35.50	1.594	E17	8.6211	E24	5.188	E19
46	34.50	1.797	E17	9.8602	E24	5.252	E19
47	33.50	2.153	E17	1.1433	E25	6.532	E19
48	32.50	2.508	E17	1.3268	E25	7.966	E19
49	31.50	2.924	E17	1.5399	E25	9.598	E19
50	30.50	3.432	E17	1.7922	E25	1.157	E20
51	29.50	4.014	E17	2.0875	E25	1.334	E20
52	28.50	4.722	E17	2.4374	E25	1.498	E20

TABLE 6-1

TOTAL MOLECULAR THICKNESSES FOR RAYS 1 - 80 (contd)

Ray(i)	Altitude h_{ii} (km)	$\tilde{n}_{air}$ ($\frac{\text{Molecules}}{\text{cm}^3}$)		Molecular Thickness (Entire Ray)			
				Air		Ozone	
53	27.50	5.564	E17	2.8522	E25	1.658	E20
54	26.50	6.573	E17	3.3453	E25	1.819	E20
55	25.50	7.696	E17	3.9188	E25	1.970	E20
56	24.50	9.339	E17	4.6402	E25	2.114	E20
57	23.50	1.069	E18	5.4305	E25	2.132	E20
58	22.50	1.248	E18	6.3479	E25	2.058	E20
59	21.50	1.456	E18	7.4188	E25	1.971	E20
60	20.50	1.710	E18	8.6849	E25	1.875	E20
61	19.50	2.000	E18	1.0164	E26	1.780	E20
62	18.50	2.339	E18	1.1892	E26	1.669	E20
63	17.50	2.737	E18	1.3913	E26	1.563	E20
64	16.50	3.201	E18	1.6276	E26	1.470	E20
65	15.50	3.745	E18	1.9041	E26	1.389	E20
66	14.50	4.382	E18	2.2276	E26	1.320	E20
67	13.50	5.126	E18	2.6059	E26	1.264	E20
68	12.50	5.998	E18	3.0486	E26	1.219	E20
69	11.50	7.019	E18	3.5668	E26	1.179	E20
70	10.50	8.082	E18	4.1521	E26	1.143	E20
71	9.50	9.145	E18	4.7927	E26	1.112	E20
72	8.50	1.031	E19	5.4980	E26	1.083	E20
73	7.50	1.159	E19	6.2775	E26	1.058	E20
74	6.50	1.299	E19	7.1386	E26	1.034	E20
75	5.50	1.451	E19	8.0872	E26	1.013	E20
76	4.50	1.616	E19	9.1297	E26	9.925	E19
77	3.50	1.796	E19	1.1283	E27	9.740	E19
78	2.50	1.991	E19	1.2603	E27	9.567	E19
79	1.50	2.201	E19	1.3320	E27	9.405	E19
80	0.50	2.427	E19	1.3727	E27	9.254	E19

For present considerations, it is assumed that when the transmitted intensity falls within the range

$$0.05 I_o(\lambda_j) \leq I_i(\lambda_j) \leq 0.95 I_o(\lambda_j) \quad (6-2)$$

the intensity ratio can be measured with sufficient accuracy to determine the optical thickness, $\tau_i(\lambda_j)$. (A more exact range of intensity ratios will be specified upon the completion of a detector sensitivity, and signal-to-noise analysis which is discussed in Section 6.6.) The criterion described by the above inequality, when used in conjunction with the data in Table 6-1, serves to define the wavelengths that can be usefully monitored. This can be illustrated by evaluating the optical thickness for the 2900Å component of various rays passing through the earth's atmosphere.

Table 6-2 summarizes the air and ozone molecular thicknesses, for rays number 12 through 31, as well as the contributions to the optical thickness by each type of molecule. The optical thickness of air is the product of the molecular thickness and β , the Rayleigh scattering cross-section per molecule, ($\beta(2900\text{Å}) = 5.763 \times 10^{-26} \text{ cm}^2$). The ozone optical thickness is the product of the total ozone molecular thickness and the absorption cross-section $\sigma(\sigma(2900\text{Å}) = 1.196 \times 10^{-18} \text{ cm}^2)$. The sum of these two products, τ_i or the total optical thickness, gives a measure of the attenuation of the 2900Å component of the i th ray, i.e., as in equation 6-1. The range of values of τ_i which appears in Table 6-2 ensure that the inequality of equation 6-2 is satisfied for the rays 12 through 31. For rays 1 through 11, the transmitted intensity at 2900Å would be greater than 9% of the incident intensity and hence would not be suitable for measuring the optical (and therefore the molecular) thicknesses. For rays 32 through 80, the attenuation rapidly increases and little or no radiation would be transmitted. Thus, it is seen that monitoring solar radiation at 2900Å could provide useful data only for the rays shown in Table 6-2

TABLE 6-2

Ray (i)	Altitude (km)	OPTICAL THICKNESS AT 2900Å FOR RAYS 12-31			
		<u>Molecular</u> <u>Air</u>	<u>Thickness</u> <u>Ozone</u>	<u>Optical Thickness</u> <u>Air</u>	<u>Optical Thickness</u> <u>Ozone</u> (2900Å)
31	49.50	1.402X10 ²⁴	2.176X10 ¹⁸	0.0808	2.6025
30	50.50	1.246X10 ²⁴	1.769X10 ¹⁸	0.0718	2.1145
29	51.50	1.108X10 ²⁴	1.438X10 ¹⁸	0.0639	1.7195
28	52.50	9.866X10 ²³	1.168X10 ¹⁸	0.0569	1.3969
27	53.50	8.796X10 ²³	9.494X10 ¹⁷	0.0507	1.1356
26	54.50	7.861X10 ²³	7.717X10 ¹⁷	0.0453	0.9230
25	55.50	7.011X10 ²³	6.280X10 ¹⁷	0.0404	0.7510
24	56.50	6.243X10 ²³	5.129X10 ¹⁷	0.0360	0.6135
23	57.50	5.546X10 ²³	4.135X10 ¹⁷	0.0320	0.4946
22	58.50	4.917X10 ²³	3.330X10 ¹⁷	0.0283	0.3983
21	59.50	4.349X10 ²³	2.669X10 ¹⁷	0.0251	0.3192
20	60.50	3.838X10 ²³	2.120X10 ¹⁷	0.0221	0.2536
19	61.50	3.379X10 ²³	1.688X10 ¹⁷	0.0195	0.2015
18	62.50	2.966X10 ²³	1.338X10 ¹⁷	0.0171	0.1601
17	63.50	2.597X10 ²³	1.064X10 ¹⁷	0.0150	0.1273
16	64.50	2.267X10 ²³	8.462X10 ¹⁶	0.0131	0.1012
15	65.50	1.972X10 ²³	6.722X10 ¹⁶	0.0114	0.0804
14	66.50	1.710X10 ²³	5.334X10 ¹⁶	0.0099	0.0638
13	67.50	1.478X10 ²³	4.238X10 ¹⁶	0.0085	0.0507
12	68.50	1.271X10 ²³	3.368X10 ¹⁶	0.0073	0.0403
					<u>Total</u>
					2.6833
					2.1863
					1.7834
					1.4538
					1.1863
					0.9683
					0.7914
					0.6495
					0.4978
					0.4266
					0.3443
					0.2757
					0.2210
					0.1772
					0.1423
					0.1143
					0.0918
					0.0737
					0.0592
					0.0476

(at least for the ozone and air distributions which were used in this sample calculation.) More generally, it can be shown that any wavelength that is monitored will provide useful data for a limited number of rays. The reason for this can be seen by examining the range of values of molecular ozone thicknesses appearing in Table 6-1. Since these values vary in magnitude from about 10^{15} to about 10^{20} , and since the desired optical thickness is of the order of unity, wavelengths should be chosen such that the ozone absorption cross-sections vary in magnitude by about four or five orders of magnitude.

The ozone absorption cross-sections in the visible and UV spectral regions do in fact vary from about $4 \times 10^{-21} \text{ cm}^2$ at $6000\text{\AA}$ to about $1 \times 10^{-17} \text{ cm}^2$ at $2600\text{\AA}$. When the Rayleigh scattering attenuation is also taken into account, it can be shown that a wavelength can always be found such that values of $\tau_1(\lambda)$ which are consistent with the criterion expressed by equation (6-2) will be obtained for rays passing as high as 76.5 km above S_u . It can further be shown that only a limited number of wavelengths are required for measuring the optical thicknesses of all of the rays shown in Table 6-1. One such possible set of wavelengths is listed in Table 6-3, together with the ozone absorption cross-sections per molecule and the Rayleigh scattering cross-sections for air molecules.

The wavelengths listed in the above table constitute a representative set. The final selection will take into account such factors as the possible presence of Fraunhofer lines in the solar spectrum, the possible presence of absorption or emission by other atmospheric constituents such as atmospheric sodium or nitric oxide, etc. Detector system requirements and limitations will also have to be considered.

In addition to the need for monitoring different wavelengths because of the spectral dependence of the optical thickness, τ_1 , it is required

TABLE 6-3
ATTENUATION CROSS-SECTIONS

$\lambda(\text{\AA})$	$\sigma(\lambda), \text{Ozone}(\text{cm}^2)$	$\beta(\lambda), \text{Air}(\text{cm}^2)$
2600	1.0136×10^{-17}	8.922×10^{-26}
2700	6.873×10^{-18}	7.674×10^{-26}
2800	3.405×10^{-18}	6.640×10^{-26}
2900	1.196×10^{-18}	5.763×10^{-26}
3000	3.192×10^{-19}	5.034×10^{-26}
3050	1.604×10^{-19}	5.380×10^{-26}
3100	9.267×10^{-20}	5.739×10^{-26}
4800	0.900×10^{-21}	7.682×10^{-27}
6000	4.355×10^{-21}	3.147×10^{-27}

that two wavelengths be monitored at each instant in order to separate the two individual contributions to the total attenuation. This can be seen by considering the following two equations:

$$I_i(\lambda_1) = I_o(\lambda_1)e^{-N_i(O_3)\sigma(\lambda_1)+N_i(\text{air})\beta(\lambda_1)} \quad (6-3)$$

$$I_i(\lambda_2) = I_o(\lambda_2)e^{-N_i(O_3)\sigma(\lambda_2)+N_i(\text{air})\beta(\lambda_2)} \quad (6-4)$$

In equations (6-3) and (6-4), $N_i(O_3)$ and $N_i(\text{air})$ represent, respectively, the total number of ozone and air molecules, per unit cross-sectional area, encountered by the i th ray in its path through the atmosphere.

If it is assumed that the $\sigma(\lambda_j)$ and $\beta(\lambda_j)$ are known exactly, then equations (6-3) and (6-4) can be solved for the two unknowns, $N_i(O_3)$ and $N_i(\text{air})$. Thus, two wavelengths, for which the inequality of equation (6-2) are simultaneously satisfied, must be monitored for each ray.

Table 6-4 shows that if $2900\text{\AA}$ is one of the wavelengths monitored for the rays 12 through 31, the second wavelength could be at $2800\text{\AA}$ for some of these rays and/or at $3000\text{\AA}$ for others. The table also illustrates that with each of three wavelengths chosen, $2800\text{\AA}$, $2900\text{\AA}$, and $3000\text{\AA}$, measurable attenuations would result for rays 17 through 26. Thus, the possibility exists of obtaining two independent measurements of the air and ozone profiles through the altitude range represented by these rays. This is shown in a more general way in Fig. 6-2 for twelve visible and UV wavelengths. This figure graphically shows that measurable attenuations will result at two or more wavelengths for any tangential ray path through the atmosphere passing as high as 70-75 km above S_u .

TABLE 6-4
TOTAL OPTICAL THICKNESS AND TRANSMISSION

Ray (i)	Altitude (km)	(2800Å)		(2900Å)		(3000Å)	
		τ	T	τ	T	τ	T
31	49.50	--	.05	2.6833	0.068	0.7653	0.465
30	50.50	--	.05	2.1863	0.113	0.6272	0.534
29	51.50	--	.05	1.7834	0.168	0.5147	0.598
28	52.50	--	.05	1.4538	0.234	0.4225	0.655
27	53.50	--	.05	1.1863	0.305	0.3424	0.710
26	54.50	2.6799	0.069	0.9863	0.373	0.2859	0.751
25	55.50	2.1848	0.112	0.7914	0.453	0.2357	0.790
24	56.50	1.7880	0.167	0.6495	0.522	0.1951	0.823
23	57.50	1.4449	0.236	0.4978	0.608	0.1599	0.852
22	58.50	1.1666	0.311	0.4266	0.653	0.1311	0.877
21	59.50	0.9456	0.388	0.3443	0.709	0.1071	0.898
20	60.50	0.7545	0.470	0.2757	0.759	0.0835	0.920
19	61.50	0.6025	0.547	0.2210	0.802	0.0708	0.932
18	62.50	0.4812	0.618	0.1772	0.838	0.0576	0.944
17	63.50	0.3847	0.681	0.1423	0.867	0.0471	0.954
16	64.50	0.3078	0.735	0.1143	0.892		>.96
15	65.50	0.2461	0.782	0.0918	0.912		>.96
14	66.50	0.1931	0.824	0.0737	0.929		>.96
13	67.50	0.1541	0.847	0.0592	0.943		>.96
12	68.50	0.1231	0.884	0.0476	0.954		>.96

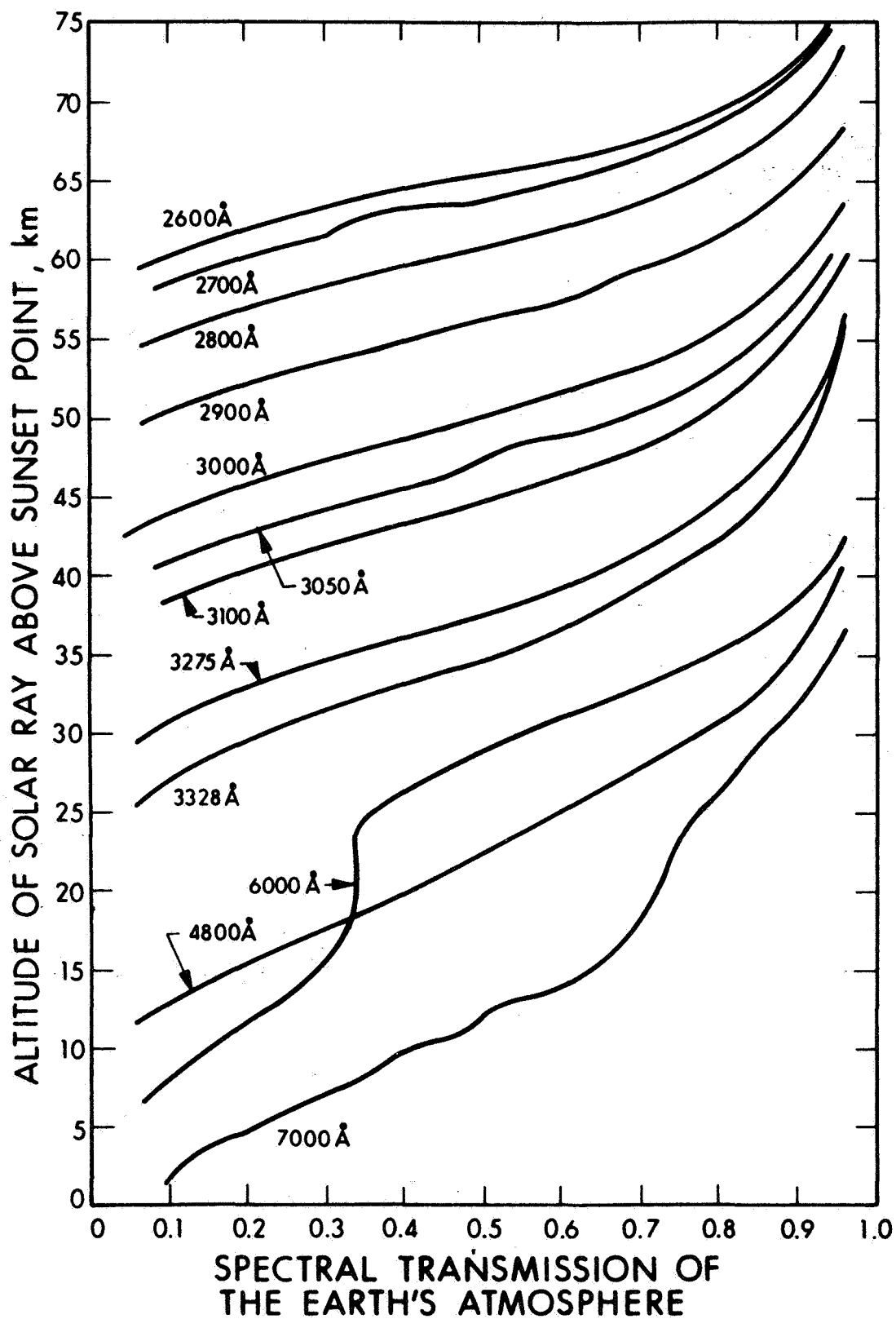


Figure 6-2. Transmission of Earth's Atmosphere for Various Tangential Solar Rays

The above discussion serves to describe the type of analyses which have been undertaken in connection with the method of differential attenuation of solar radiation. In addition to the selection of wavelengths, other aspects under investigation are: (1) an estimate of the accuracy of the technique which takes into account both the inherent uncertainty in the values of the pertinent cross-sections and the accuracy with which the intensity ratios $I_i(\lambda_j)/I_o(\lambda_j)$ can be measured, (2) the number of rays which can reasonably be expected to be measured during a satellite's passage through the sunset and sunrise portions of its orbit, (3) the amount of global coverage that would result from the implementation of such a measurement technique aboard an orbiting satellite. The coverage to be defined will include the number of locations above which the vertical ozone profile would be determined during one day, and the frequency at which such measurements would be made above any given location (4) the analytical techniques which will allow the vertical ozone distribution to be deduced from a measurement of the intensity ratios $I_i(\lambda_j)/I_o(\lambda_j)$. This involves essentially the simultaneous solution of n equations of the type represented by equations (6-3) and (6-4) where n is the number of rays at which the intensity ratio measurements are taken. (The n unknowns are the contributions to $N_i(O_3)$ and $N_i(\text{air})$ made by the n spherical shells for each of the n rays.) This analysis will be performed with the aid of the modified INVOZONE computer program, (5) the complications introduced by the finite size of the sun and by atmospheric refraction are being analyzed, (6) instrument design studies based on the wavelength selection considerations have been initiated. These aspects are discussed in the following subsections.

6.4 IMPLICATIONS OF THE DEVIATION OF THE SOLAR DISC FROM A POINT SOURCE

The fact that the sun cannot be treated as a point source in the application described above has previously been considered to be an inherent

limitation of this measurement technique^{172,173,174}. However, an investigation of the problem indicates that the opposite may be true. Rather than representing a limitation, the finite size of the sun's image may be used to advantage due to the fact that the image represents a large number of point (or line) sources with different paths through the atmosphere. The extent of this variation in paths can be appreciated by reference to Fig. 6-3. The position of this satellite is represented by the point B in this figure, and is assumed to be at some known altitude h_s . The extreme rays of the sun are represented by the paths D_1H_1 and QP . The range of altitudes, Δh , directly above the sunset point which is defined by these extreme rays is represented by the line segment K_1K_3 . For simplicity, the earth's atmosphere is divided into 3 shells only.

The solar radius, R , from center to limb is known to be equal to $6.957 (\pm .001) \times 10^5$ km. The distance from the earth to the sun, approximately equal to A.U., the astronomical unit, is taken as 1.4953×10^8 km. Therefore, the sun, as observed by a satellite at a distance AB from a location directly above the sunset point, is not a point source but a disc which subtends an angle α at the satellite, where

$$\sin(\alpha/2) = \frac{R}{A.U. + AB} \approx \frac{R}{A.U.} = \frac{6.957 \times 10^5}{1.495 \times 10^8} = 4.653 \times 10^{-3}$$

$$\alpha/2 \approx 16'$$

$$\alpha = (\beta_1 + \beta_3) \approx 32' , \text{ for } AB \ll A.U.$$

This represents a vertical range described by the extreme rays of the sun above the sunset point of Δh :

$$\Delta h = 2AB (4.65 \times 10^{-3}) \text{ km} = 9.30 \times 10^{-3} AB \text{ km.}$$

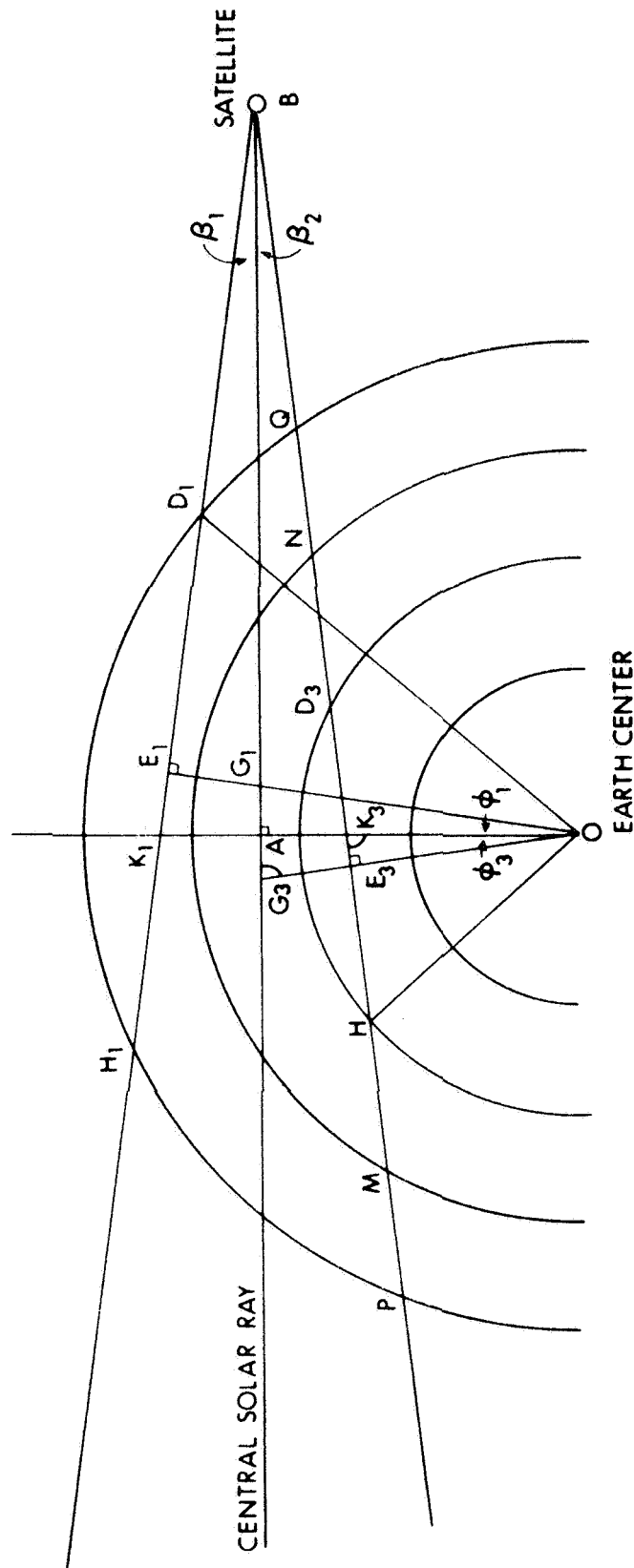


Figure 6-3. Geometry of Solar Rays Traversing Earth's Atmosphere Without Refraction as Observed by a Satellite

Taking the earth's radius as 6375 km, and for a satellite orbital altitude of h_s , the following relationship between h_s and Δh results.

$$\Delta h = 9.30 \times 10^{-3} \left[(6375 + h_s)^2 - (6405)^2 \right]^{1/2} \text{ km.}$$

The altitude range above the sunset point defined by the extreme rays are shown in Table 6-5 for a number of orbital altitudes.

TABLE 6-5

h_s (km)	Δh (km)
200	13.8
400	20.5
600	25.7
800	30.1
1000	34.0
1500	42.6

It can be seen that for any anticipated satellite altitude, the range of altitudes Δh is large with respect to even the coarsest spatial resolution requirements. The analyses of the preceding subsections, on the other hand, are essentially valid only if the tangential or central ray BG_1G_3 is used for the measurement of solar intensities. However, this represents no insurmountable obstacle since optics can be designed which select only a slice of the solar image whose path through the atmosphere approximates that of the central ray. The intensity of solar radiation can be shown to be such that a reduction of 20 or 30 due image-slicing can be tolerated. That is, the large signal-to-noise ratios will still be obtained if photomultiplier detection techniques are used.

However, rather than being limited to the selection of the central ray, a variety of rays could be optically isolated or the entire solar disc could be scanned for any instantaneous position of the satellite. That is, superimposed upon the scanning provided by motion of the satellite a supplementary scanning of the solar disc can be obtained optically. Since this ozone measuring technique is self-calibrating (i.e., the intensity of solar radiation from a segment of the solar disc is measured first when the earth's atmosphere does not intervene and then after it passes through a known path through the atmosphere), the total number of ozone and air molecules can be measured for these additional non-tangential, or slant, paths through the atmosphere. The additional information obtained from these slant paths can be useful in determining any significant departures from spherical symmetry in the ozone concentrations in the individual shells.

This can be most easily shown by referring again to Fig. 6-3. The ozone concentrations in the three shells could be determined by allowing the satellite motion to scan the atmosphere, i.e., select the rays passing through the centers of shells 1, 2, and 3 at three successive satellite positions. This is essentially the technique which has been described in detail in previous portions of this section. An alternate approach would be to allow the satellite, when at the position B, to view the three rays shown in the figure, the central ray, and the two extreme rays. The traverse length of these rays in each shell can again be determined from geometrical principles. This geometry exercise will not be presented in detail here; the important results are:

1. If β_j is the angle that the j th ray makes with the central ray, and h_j is the distance of the central ray from the center of the earth, then the distance of the j th ray from the center of the earth is given by

$b_j = AB \sin \beta_j - (h_j / \cos \beta_j)(\sin^2 \beta_j - 1)$, for rays above the central ray and,

$b_j = -AB \sin \beta_j - (h_j / \cos \beta_j)(\sin^2 \beta_j - 1)$, for rays below the central ray. If angles for rays below the central ray are given a negative sign

$$b_j = AB \sin \beta_j - \frac{h_j}{\cos \beta_j} (\sin^2 \beta_j - 1), \text{ for all } j.$$

2. If a_{ji} denotes the length that the j th ray traverses in the i th shell, whose top boundary is at a distance c_i from the earth's center, then

$$1/2 a_{ji} = \left[c_i^2 - b_j^2 \right]^{1/2} - \sum_{l=i+1}^j a_{jl}$$

3. The results obtained in this form can be used in INVOZONE, with minor programming modifications, to yield the vertical profile of the ozone concentrations.

Two essentially independent means of measuring the ozone profile by the differential attenuation technique thus exist. They differ only in the method of scanning the atmosphere. In actual practice, the optimum technique will probably prove to be one which combines both methods of scanning.

In the sample example discussed above, the vertical distribution consists of three concentration values, one for each shell. If the concentration were, in fact, uniform within each shell, the two techniques would yield exactly the same distributions. If different results were obtained by the two methods, however, the assumption of spherical symmetry would obviously be suspect. By comparing the exact paths of each ray in the individual shells, an indication of the locations of

anomalously high or low concentration regions within a shell could be obtained. More information could be obtained by sampling more than just three rays, say seven or eight, at one satellite position. Finally, by performing an optical scan of the entire solar disc at a large number of satellite positions, a high-resolution mapping of the vertical and horizontal ozone distribution could in principle be obtained.

The actual number of rays that are measured in any given satellite passage will, therefore, be determined, in the optimum case, by detector, optical scanning, data recording, reduction, and telemetry limitations. It nevertheless is evident that by exploiting the finite size of the sun's image, the need for assuming spherically symmetric atmospheric shells can in large part be eliminated.

6.5 THE ATMOSPHERIC DISPERSION PROBLEM

The subject of atmospheric refraction was for many years one of the most widely studied problems in astronomy. Simon¹⁷⁵ has recently reviewed the problem, with emphasis on the wavelength dependence (atmospheric dispersion) of the refraction for rays which can be considered to be near-tangential (zenith angles greater than 80°). In earth-bound observations of rays entering the earth's atmosphere from a direction near the horizon, the violet light appears to come from a point nearer the horizon than the red. This must be compensated for either in the reduction of data or by some compensating optics, which exactly shift the two wavelengths of interest by an amount equal to the atmospheric dispersion, before the two wavelengths enter the slit of the recording instrument. In either case, the correct magnitude of the atmospheric dispersion must be known.

In addition to this dispersion problem, atmospheric refraction can introduce two sources of error in the satellite application of the

differential attenuation technique. For a given wavelength component of a ray traversing the earth's atmosphere, refraction can, if not properly accounted for, cause erroneous values to be assumed for:

1. The altitude at which the ray of interest passes above the sunset point, and
2. the lengths traversed by the rays in the individual atmospheric shells.

These problems have been analyzed by Venkateswaran, et. al.¹⁷⁴ who show that the refraction effects can be corrected. Simon¹⁷⁵ also shows that the magnitude of the refraction as a function of wavelength can be computed to any reasonably desired accuracy.

6.6 OZONE SIGNAL DETECTION AND MEASUREMENT

Optical detection of attenuated UV and visible solar radiation, in connection with the passive ozone measurement technique described in previous subsections, is quite straightforward and capable of providing high measurement accuracy and precision. In particular, accurate measurements of ozone concentration are achievable since large optical signals are obtained from viewing the solar flux directly after it has been transmitted through the earth's atmosphere. Furthermore, since the sun is the signal source and is viewed directly, the optical receiver in the satellite can be designed to have a field of view which is sufficiently small so that major sources of noise and measurement errors are significantly reduced; and, in addition, the optical receiver spectral bandwidth can be as narrow as practicable so that spectral intensities can be measured with fine spectral resolution. Still further, the available signal intensity and the satellite orbit and measurement geometry are such that several wavelengths can be scanned at modest rates and signals integrated over reasonable times to ensure adequate measurement sensitivity and accuracy.

The subsections which follow contain quantitative discussions of signal detection and factors that affect the measurement system sensitivity and accuracy.

6.6.1 SIGNAL DETECTION

The magnitude of the solar flux that reaches the satellite when the sun's rays are tangential to the earth's atmosphere depend upon the azimuthal position of the satellite with respect to the earth, as was shown in Fig. 6-1. The satellite is shown in a position that is intermediate between the measurement positions of maximum and minimum solar flux attenuation by the earth's atmosphere. As the satellite

makes its transit through each tangential incremental altitude, the sun is tracked and the spectral intensities at several selected UV and optical wavelengths are measured sequentially. In this section we derive an expression for the optical receiver system signal-to-noise ratio (SNR), make certain assumptions about the system design, and then evaluate the system performance.

The optical receiver is assumed to consist simply of an objective lens, a field stop, selectable narrowband optical filters, and a photodetector. The photodetector can be either the photoemissive or solid-state type photodetector, which is sensitive over the spectral region from about 0.25μ to 0.65μ . For the present we consider a photoemissive detector which allows a wide dynamic signal detection range. The overall performance of the optical receiver is determined by the system SNR.

The solar flux on the photodetector produces a photocurrent which is proportional to the intensity of the incident radiation, P_s , given by

$$I_s = \frac{e \eta_D P_s}{h\nu} \quad (6-5)$$

where η_D = detector quantum efficiency
 e = electronic charge
 $h\nu$ = energy per photon

The intensity of the solar radiation at the photodetector is given by

$$P_s = T_A T_O A_R \Delta_\lambda H_\lambda \text{ (watts)} \quad (6-6)$$

where H_λ = solar spectral irradiance outside the earth's atmosphere
in watts/cm²/Å
 Δ_λ = spectral bandwidth of optical filter
 A_R = objective aperture
 T_O = optical system transmission
 T_A = atmospheric transmittance function

Combining Eqs. 6-5 and 6-6 and assuming that a photomultiplier is used with internal gain, G_D , the output signal voltage across the detector load resistor, R_L , is given by

$$V_S = \left(\frac{e T_O A_R \Delta_\lambda \eta_D G_D R_L H_\lambda}{h\nu} \right) T_A \quad (6-7)$$

Equation 6-9 expresses the responsivity of the system; however, of additional interest is the minimum detectable signal.

The signal voltage must exceed the noise voltage of the optical receiver. For the case of the photomultiplier, assuming noiseless multiplication, the noise of the detector load consists of shot noise produced in the photodetection process and thermal noise produced by the load resistor.

The optical system signal-to-noise ratio is expressed by

$$SNR = \frac{I_S}{\sqrt{2e I_t \Delta f + 4F_k T \Delta f / G_D R_L}} \quad (6-8)$$

where $I_t = I_S + I_{BG} + I_d$
 I_{BG} = photocurrent produced by background sources
 I_d = detector dark current
 F = postdetection noise figure
 k = Boltzmann's constant
 T = temperature
 Δf = electronic bandwidth

Assume that the optical receiver is signal shot noise limited; i.e.,
 $I_S \gg I_d \gg I_{BG}$ and $2e I_S \Delta f \gg 4F_k T \Delta f / G_D R_L$.

Equation 6-8 now becomes

$$SNR = \left(\frac{I_S}{2e \Delta f} \right)^{1/2} = \left(\frac{T_A T_o A_R \Delta_\lambda \eta_D H_\lambda}{2h\nu \Delta f} \right)^{1/2} \quad (6-9)$$

The minimum detectable solar flux is given by Eq. 6-9 for the case where $SNR = 1$. More realistically, the SNR should be greater than unity at a value which is consistent with desired system measurement accuracy. It is apparent from Eq. 6-9 that the minimum detectable signal is determined also by the spectral resolution and sampling rate requirements imposed on the measurements.

For the case just considered, where the optical receiver is signal shot noise limited, the minimum detectable signal is determined by the detector noise equivalent power, NEP, which in turn depends upon the electronic bandwidth requirements of the measurements, given by

$$P_{S_{min}} = NEP = \frac{[A_D \Delta f]^{1/2}}{D^*} \quad (\text{watts}) \quad (6-10)$$

where A_D = detector area
 D^* = detectivity in $\text{cm-Hz}^{1/2}\text{-watt}^{-1}$
 $\Delta f \sim \frac{2}{t_s}$ = electronic bandwidth
 t_s = period of maximum signal frequency

When the system bandwidth requirements are large such that the condition $2e I_S \Delta f \gg 4F_k T \Delta f / G_D R_L$ or when $I_S \gg I_d \gg I_{DG}$ no longer hold, then the system sensitivity must be determined from Eq. 6-8. We shall not determine the limitation to system bandwidth using the first condition, i.e.,

$$e I_S \Delta f > \frac{2 F_k T \Delta f}{G_D R_L} \quad (6-11)$$

Using Eq. 6-5, Eq. 6-11 can be rewritten

$$P_S > \frac{F_k T h\nu}{e^2 \eta_D G_D R_L} \quad (6-12)$$

where

$$P_{S_{lim}} = NEP > \frac{F_k T h\nu}{e^2 \eta_D G_D R_L} \quad (6-13)$$

The detector load resistance cannot be made arbitrarily large, however, since R_L must also satisfy the bandwidth condition

$$R_L < \frac{2}{\Delta f C_S} \quad (6-14)$$

where C_S = effective capacitance of detection system output

Combining Eqs. 6-10 and 6-13, the system electronic bandwidth must satisfy the requirements

$$\Delta f < \left(\frac{e^2 \eta_D G_D D^* R_L}{F_k T h\nu A_D^{1/2}} \right)^2 \quad (6-15)$$

or from Eqs. 6-14 and 6-15

$$\Delta f < \left(\frac{2e^2 \eta_D G_D D^*}{F_k T h\nu A_D^{1/2} C_S} \right)^{2/3} \quad (6-16)$$

Summarizing, the optimum selection of photodetector used for the measurements depends upon several factors, most important of which are detector responsivity, detectivity, and frequency response. From Eq. 6-7, it is seen that the signal voltage is proportional to detector quantum efficiency, η_D , multiplication factor, G_D , and load resistance, R_L . The latter is limited by bandwidth considerations as already discussed. In order to increase responsivity then it may be desirable to use a detector with internal gain, such as a photomultiplier, even though quantum efficiencies are typically lower than near-unity gain solid state detectors. Although internal gain does not enter directly into SNR expression (Eq. 6-9) for the case of signal limited operation, it is observed from Eq. 6-15 that internal and noiseless photocurrent gain assists in overcoming thermal noise limitations while broadening allowable electronic bandwidths.

The system electronic bandwidth must be sufficient such that small changes in solar flux are detected, consistent with measurement accuracies. Consider the satellite orbit depicted in Fig. 6-1. With the satellite at an altitude of 1000 km and an orbit velocity of about 100 km/sec, the minimum time of travel of the satellite between incremental altitudes $h_i - h_j = 1$ km is 10 millisecond. Now assume that 10 wavelengths are to be scanned during the travel through each incremental altitude and that the signal integration time per wavelength channel is 1 millisecond. The electronic bandwidth requirement for each observation is, consequently, about 2 kHz.

System performance can now be determined from Eq. 6-9 by making certain system parameter assumptions and by using known values of solar spectral irradiance. Consider the case of a photomultiplier tube (S-5 response) and an optical receiver with the following characteristics:

Receiver collecting area, $A_R = 50 \text{ cm}^2$
 Optical efficiency, $T_o = 0.5$
 Optical bandwidth, $\Delta\lambda = 10\text{\AA}$
 Detector quantum efficiency, $\eta_D = 0.18$ (at $\lambda = 2600\text{\AA}$)
 Electronic bandwidth, $\Delta f = 2000 \text{ Hz}$

Assume that the atmospheric transmittance through the maximum length of atmosphere is $T_A = 0.1$, which is a worst case value.

The solar flux at $\lambda = 2600\text{\AA}$ outside the earth's atmosphere is
 $N_\lambda = \frac{H_\lambda}{h\nu} = 0.97 \times 10^{12} \text{ photons/cm}^2\text{-sec-}\text{\AA}.$

Using Eq. 6-9, the optical system signal to noise is calculated to be

$$\text{SNR} = \frac{(0.1)(0.5)(50)(10)(0.18)(0.97 \times 10^{12})}{(2)(2000)} \sim 3 \times 10^4$$

This SNR performance is typical for a measurement solar irradiance at the lowest system sensitivity level and is suitable for reliable and accurate measurements of ozone concentration.

So far the detectability of the detection system has been discussed without detailed mention of the factors affecting the accuracy of the measurements. These factors are now analyzed briefly.

6.6.2 MEASUREMENT ACCURACY

The method of extracting ozone concentration from the measurement data will be reviewed here in order to delineate the factors affecting the measurement accuracy.

For simplicity it will be assumed that solar intensity measurements are made at spectral wavelengths where the ozone absorption is large

$I_i(\lambda_1)$ and completely negligible $I_i(\lambda_2)$, where i corresponds to the i th altitude segment. When the satellite is normal to the sun's tangential rays and in a position where the earth's atmosphere does not intervene, then reference signal intensities are recorded, i.e., $I_o(\lambda_1)$ and $I_o(\lambda_2)$.

Two ratios are formed; namely,

$$R_{io}(\lambda_2) \equiv \frac{I_i(\lambda_2)}{I_o(\lambda_2)} = e^{-N_i(\text{air}) \beta(\lambda_2)} \quad (6-17)$$

where $N_i(\text{air})$ = number of air molecules per receiver viewing area for the optical path at the i th altitude
 $\beta(\lambda_2)$ = molecular absorption cross section due to scattering by air molecules at λ_2

and

$$R_{io}(\lambda_1) \equiv \frac{I_i(\lambda_1)}{I_o(\lambda_1)} = e^{-[N_i(\text{air}) \beta(\lambda_1) + N_i(\text{O}_3) \sigma(\lambda_1)]} \quad (6-18)$$

where $\beta(\lambda_1)$ = molecular absorption cross section due to scattering by air molecules at λ_1
 $N_i(\text{O}_3)$ = number of ozone molecules per receiver viewing area for optical path at the i th altitude
 $\sigma(\lambda_1)$ = ozone absorption cross section

From Eq. 6-17,

$$N_i(\text{air}) = \frac{1}{\beta(\lambda_2)} \ln \frac{1}{R_{io}(\lambda_2)} \quad (6-19)$$

and from Eq. 6-18,

$$N_i(\text{O}_3) = \frac{1}{\sigma(\lambda_1)} \left[\ln \frac{1}{R_{io}(\lambda_1)} - N_i(\text{air}) \beta(\lambda_1) \right] \quad (6-20)$$

Combining Eqs. 6-17, 6-18, and 6-19 yields the expression for total ozone content given by

$$N_i(O_3) = \frac{1}{\sigma(\lambda_1)} \left[\ln \left(\frac{I_o(\lambda_1)}{I_i(\lambda_1)} \right) - \frac{\beta(\lambda_1)}{\beta(\lambda_2)} \ln \left(\frac{I_o(\lambda_2)}{I_i(\lambda_2)} \right) \right] \quad (6-21)$$

The measurement error in the total ozone content is obtained by differentiating Eq. 6-21 as follows:

$$\begin{aligned} d N_i(O_3) &= \frac{1}{\sigma_1} \frac{d \left(\frac{I_{o1}}{I_{i1}} \right)}{\left(\frac{I_{o1}}{I_{i1}} \right)} + \ln \left(\frac{I_{o1}}{I_{i1}} \right) \left(\frac{-d\sigma_1}{\sigma_1^2} \right) - \frac{\beta_1}{\sigma_1 \beta_2} \frac{d \left(\frac{I_{o2}}{I_{i2}} \right)}{\left(\frac{I_{o2}}{I_{i2}} \right)} - \\ &\quad \ln \left(\frac{I_{o2}}{I_{i2}} \right) \left[\frac{\sigma_1 \beta_2 d\beta_1 - \beta_1 \sigma_1 d\beta_2 - \beta_1 \beta_2 d\sigma_1}{\sigma_1 \beta_2^2} \right] \\ &= \frac{1}{\sigma_1} \left\{ \frac{d I_{o1}}{I_{o1}} - \frac{d I_{i1}}{I_{i1}} - \ln \left(\frac{I_{o1}}{I_{i1}} \right) \frac{d \sigma_1}{\sigma_1} - \frac{\beta_1}{\beta_2} \frac{d I_{o2}}{I_{o2}} + \frac{\beta_1}{\beta_2} \frac{d I_{i2}}{I_{i2}} - \right. \\ &\quad \left. \ln \left(\frac{I_{o2}}{I_{i2}} \right) \left[\frac{d \beta_1}{\beta_2} - \frac{\beta_1}{\beta_2} \frac{d \beta_2}{\beta_2} - \frac{\beta_1}{\beta_2} \frac{d \sigma_1}{\sigma_1} \right] \right\} \quad (6-22) \end{aligned}$$

The maximum error in ozone content is then

$$\begin{aligned} \Delta N_i(O_3) &= \frac{1}{\sigma_1} \left\{ \frac{\Delta I_{o1}}{I_{o1}} + \frac{\Delta I_{i1}}{I_{i1}} + \frac{\beta_1}{\beta_2} \left[\frac{\Delta I_{o2}}{I_{o2}} + \frac{\Delta I_{i2}}{I_{i2}} \right] + \ln \left(\frac{I_{o1}}{I_{i1}} \right) \frac{\Delta \sigma_1}{\sigma_1} + \right. \\ &\quad \left. \ln \left(\frac{I_{o2}}{I_{i2}} \right) \left[\frac{\Delta \beta_1}{\beta_2} + \frac{\beta_1}{\beta_2} \frac{\Delta \beta_2}{\beta_2} + \frac{\beta_1}{\beta_2} \frac{\Delta \sigma_1}{\sigma_1} \right] \right\} \quad (6-23) \end{aligned}$$

Errors are incurred in the ozone measurements due to uncertainties in measured intensities (including noise in signal), and in known values of absorption and scattering coefficients. It is observed that errors increase for increasing values of β_1/β_2 so that λ_2 should be larger than the largest wavelength selected to correspond with the ozone absorption lines; in this way, the effects of Rayleigh scattering are reduced for the longer wavelengths and β_1/β_2 is minimized.

Consider for the moment the case where absorption and scattering coefficients are accurately known. The maximum percent of error in the ozone measurement is, from Eqs. 6-21 and 6-23,

$$E_{\max} = \frac{\Delta N_i(O_3)}{N_i(O_3)} \times 100 = \frac{\left\{ \frac{\Delta I_{o1}}{I_{o1}} + \frac{\Delta I_{i1}}{I_{i1}} + \frac{\beta_1}{\beta_2} \left[\frac{\Delta I_{o2}}{I_{o2}} + \frac{\Delta I_{i2}}{I_{i2}} \right] \right\}}{\left\{ \ln \left(\frac{I_{o1}}{I_{i1}} \right) - \frac{\beta_1}{\beta_2} \ln \left(\frac{I_{o2}}{I_{i2}} \right) \right\}} \times 100 \quad (6-24)$$

Errors in intensity measurements arise from three major sources:

- a. Variations in sun's intensity across solar disc
- b. Directly and indirectly scattered solar radiation
- c. Quantum and shot noise

The sun is a relatively stable source of energy so that intensity variations due to source modulation can be neglected. On the other hand, the sun's brightness is significantly lower at the edge of the solar disc than at the center so that solar tracking errors could result in considerable variations in the solar flux being observed at the satellite. Figure 6-4 shows this limb-darkening effect; ultraviolet radiant intensity is particularly reduced at the sun's edge, where the ratio r/R is defined in Fig. 6-5.

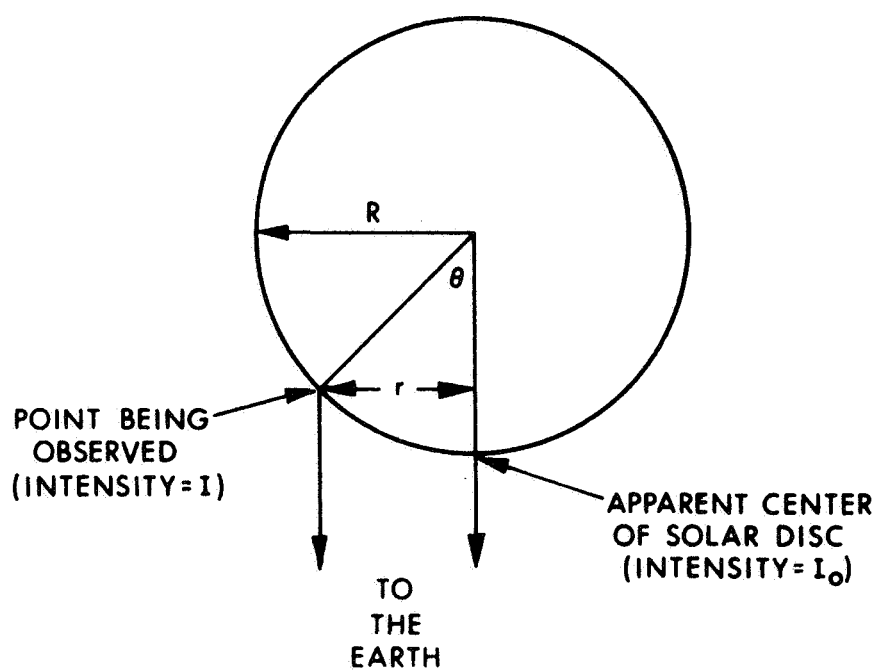


Figure 6-4. Limb Darkening Geometry

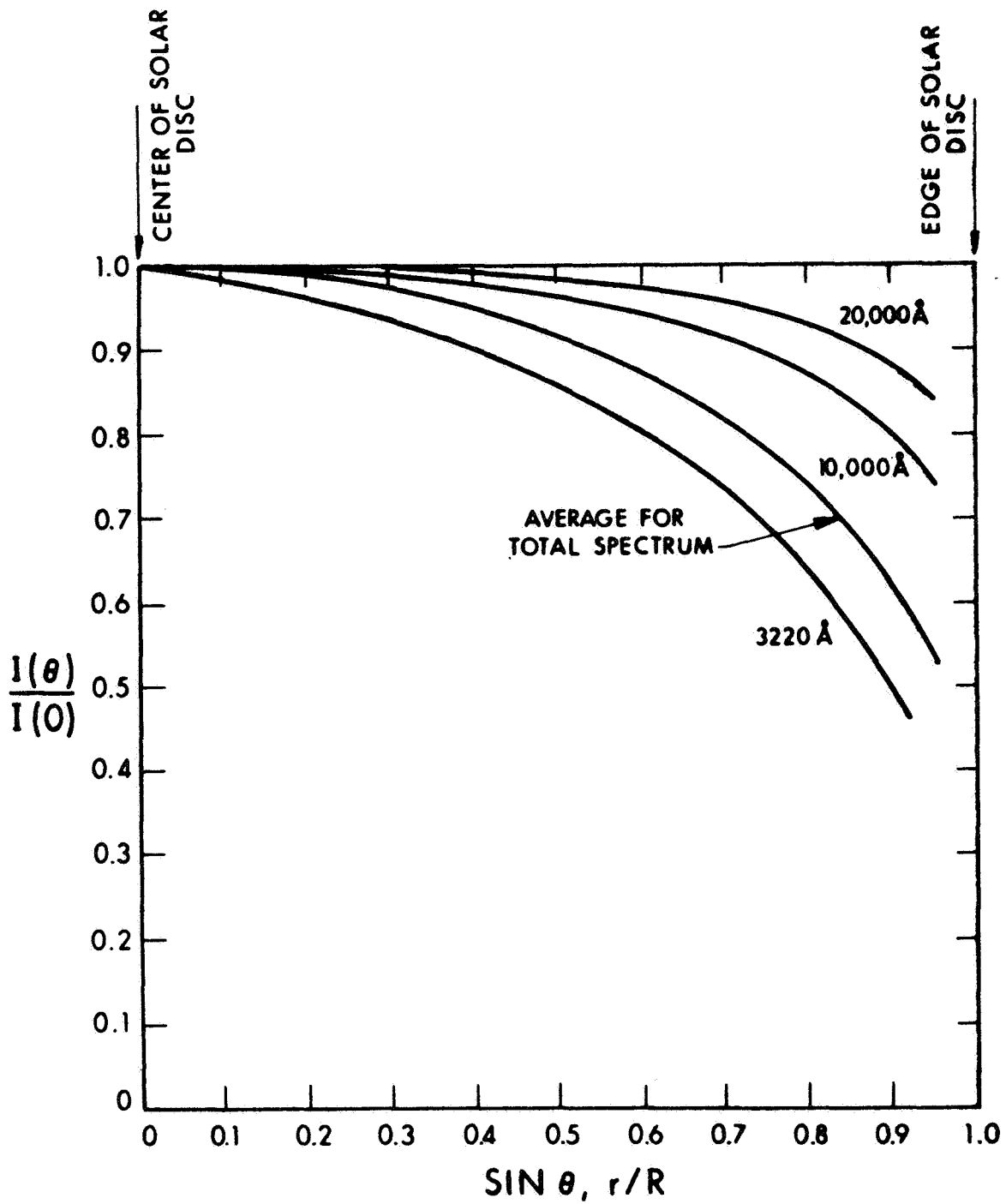


Figure 6-5. Limb Darkening Effect on Solar Disc-Intensity as a Function of Wavelength and Radial Location on Solar Disc

In order to effectively maintain constant source intensity, the sun must be accurately tracked. Furthermore, the sun must continually remain in the optical receiver's field of view during the measurement.

The field of view of the receiver is determined principally by the vertical atmospheric resolution requirements and the altitude of the satellite above the earth. As discussed in a previous report, the vertical increment observed when the satellite is at a height of 1000 km is 34 km when the full sun is observed. In order to improve this vertical resolution, one must observe only a small segment of the sun. Since ample signal-to-noise performance is achievable, then reducing the observational area of the source is practical. The resulting decrease in SNR is given by

$$\text{SNR}' = k \left(\frac{A_s}{A_T} \right) \text{SNR} \quad (6-25)$$

where

$$\begin{aligned} k &= \text{limb-darkening coefficient} \\ A_s &= \text{observed solar area} \\ A_T &= \text{total area of sun} \end{aligned}$$

Reducing the optical receiver field of view from about 32 minutes of arc to about one minute of arc has the additional advantage in that the effects of indirect and direct solar scattering are made negligible.

The major source of measurement error arises from quantum and shot noise, which from Eq. 6-9 is

$$\frac{\Delta I}{I} = \frac{N}{S} = \left(\frac{2e\Delta f}{I_s} \right)^{1/2} = \left(\frac{2h\nu\Delta f}{T_A T_O \frac{A_s}{k \frac{A_T}{A_R} \Delta_\lambda \eta_D H_\lambda}} \right)^{1/2} \quad (6-26)$$

SECTION 7

RAMAN LASERS AS ACTIVE OZONE PROBES

In the long history of ozone measurements by optical techniques, few attempts to use active probes have been made. The various schemes which have been developed or proposed in the past depend mainly on either direct, indirect, reflected, or scattered solar radiation. However, the use of active probes as practical, accurate, and reliable ozone measuring devices has recently become feasible with the advent of the laser. This device emits radiation which is coherent, highly directional, monochromatic, and very intense. This combination of properties warrants serious consideration of the laser for measurements of atmospheric properties. The backscattering of laser radiation has, in fact, recently been used as a means of probing the atmosphere. However, the monochromaticity of laser radiation has proved to be a limitation on the type of information that can be derived from backscattering data.

Since very few materials are capable of emitting pulsed, high-power laser radiation, few wavelengths of intense laser radiation would be available were it not for the phenomenon known as stimulated Raman scattering (this phenomenon will be referred to as SRS and the resulting radiation as Raman laser radiation.) This effect can be exploited to generate intense laser-like radiation at a wide variety of wavelengths and, therefore, to greatly extend the potential usefulness of lasers for atmospheric probes. A brief review of the physics involved in SRS is presented in the following subsection.

Following this, an outline of various methods in which Raman laser radiation could be used to measure the atmospheric ozone content is presented. Subsection 7.3 deals with details of experimental measurements which have been performed for the express purpose of producing wavelengths of Raman laser radiation which coincide with those in the ozone absorption bands. Calculations which show the feasibility of an active probe technique involving ground-based Raman lasers and satellite-based detectors are presented in Subsection 7.4.

7.1 STIMULATED RAMAN SCATTERING AND RAMAN LASERS

The inelastic scattering of photons by molecules is known as Raman scattering. As a result of the act of scattering, an incident photon of energy $h\nu$ is transformed into a scattered photon of energy $h\nu'$. The energy difference, $h|\nu-\nu'|$, represents the separation between a pair of electronic, vibrational, or rotational levels of the scattering molecule. The most commonly encountered forms of Raman scattering involve the latter two types of molecular energy levels. The normal or spontaneous Raman spectrum of a molecule, i.e., that excited by an incoherent source of radiation, generally consists of many spectral lines, each of which is separated from the exciting frequency by the frequency of a vibrational or rotational transition. The number of lines in the normal Raman spectrum depends on the number of atoms in the molecule and on the symmetry of the latter. Figure 7-1 shows the normal vibrational spectra of H_2 and D_2 , and Fig. 7-2 shows the normal rotational spectrum of hydrogen.

When giant-pulsed, high intensity laser radiation is used to produce Raman scattering, instead of incoherent radiation from conventional sources, the dominant scattering process may be induced, or stimulated, Raman scattering (SRS). The occurrence of SRS depends

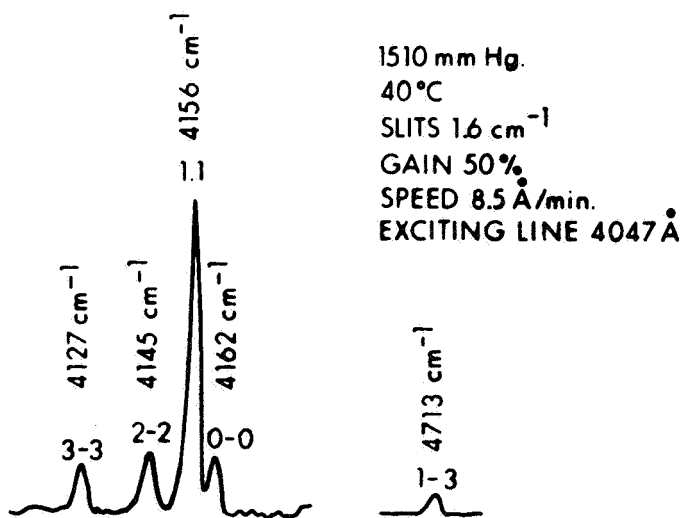
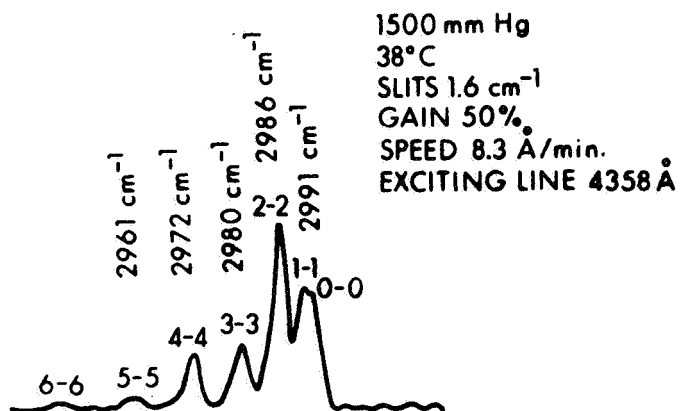
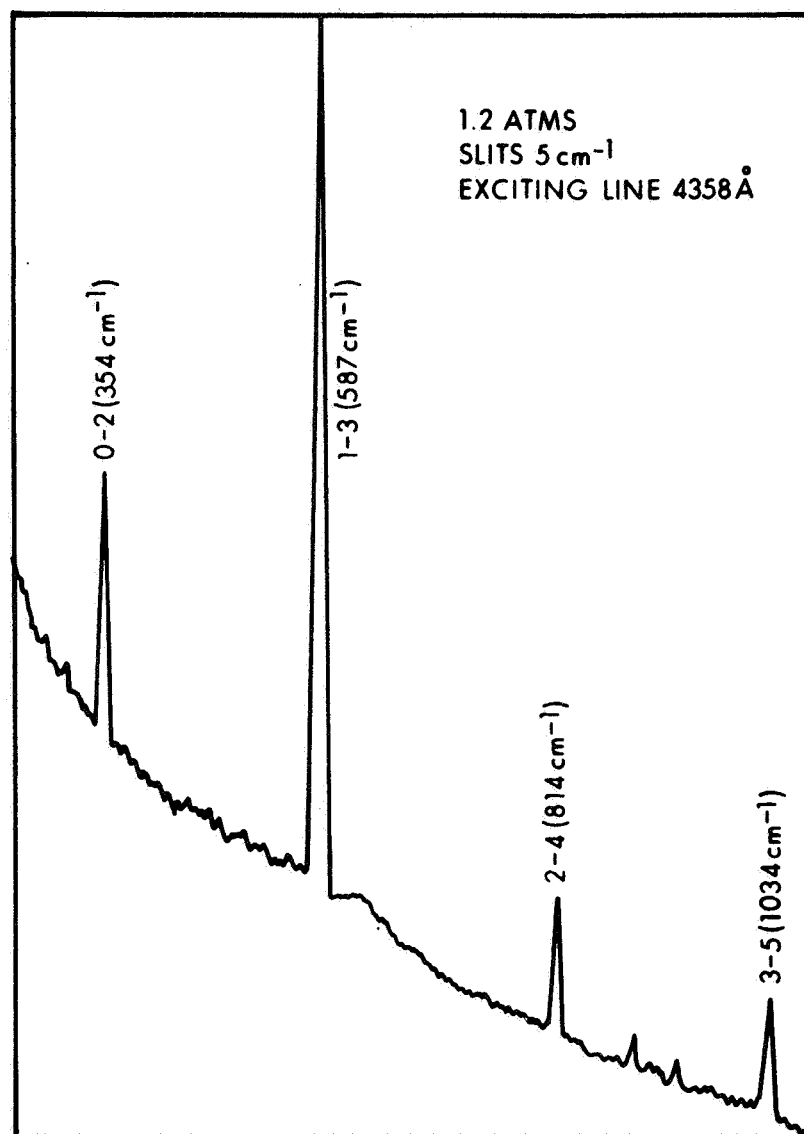


Figure 7-1. The Normal Raman Vibrational Spectra of D₂ and H₂



INTENSITY RATIOS OF HYDROGEN ROTATIONAL RAMAN LINES

		<u>OBSERVED</u>	<u>THEORETICAL</u>
ORTHO HYDROGEN	$\frac{3 \rightarrow 5 (1035 \text{ cm}^{-1})}{1 \rightarrow 3 (588 \text{ cm}^{-1})}$	0.112	0.112
PARA HYDROGEN	$\frac{2 \rightarrow 4 (814 \text{ cm}^{-1})}{0 \rightarrow 2 (355 \text{ cm}^{-1})}$	0.438	0.458

Figure 7-2. The Pure Rotational Normal Raman Spectrum of H_2

on the presence of a high density of both incident and Raman-scattered photons and thus had not been observed prior to the development of the laser. Several important differences are observed in the normal and stimulated Raman spectra of any given substance:

- a. Only one or two molecular transitions usually participate in SRS. For example, in the SRS spectrum of hydrogen as produced by ruby laser excitation only the Q(1) transition at 4156 cm^{-1} (see Fig. 7-1) appears. This can be seen in Fig. 7-3 which shows the anti-Stokes SRS spectrum of H_2 .
- b. The efficiency of the Raman process dramatically increases when the transition from normal to stimulated scattering occurs. As much as 50% of the incident radiation may be transformed into Raman shifted wavelengths in SRS, whereas the normal scattering converts only a small fraction of a percent of the incident radiation.
- c. In addition to frequency shifts given by $\Delta\nu = |\nu - \nu'|$, where $\Delta\nu$ is the frequency of the molecular transition excited in SRS, the scattered radiation contains components at the frequencies $\nu_L \pm n\Delta\nu$, where ν_L is the frequency of the incident laser and $n = 0, 1, 2, \dots$. Thus, the emission line at $4400\text{\AA}$ which is seen in Fig. 7-3 corresponds to $\nu_L + 2\Delta\nu$ and is referred to as the second anti-Stokes line of H_2 in SRS.
- d. The SRS radiation is highly directional, many components having essentially the same angular divergence as that of the initial laser radiation. This is a consequence of the fact that SRS involves the induced emission of radiation by molecules.

The shifts, $\Delta\nu$, most commonly produced in SRS correspond to molecular vibrational frequencies and so their magnitudes vary, depending on

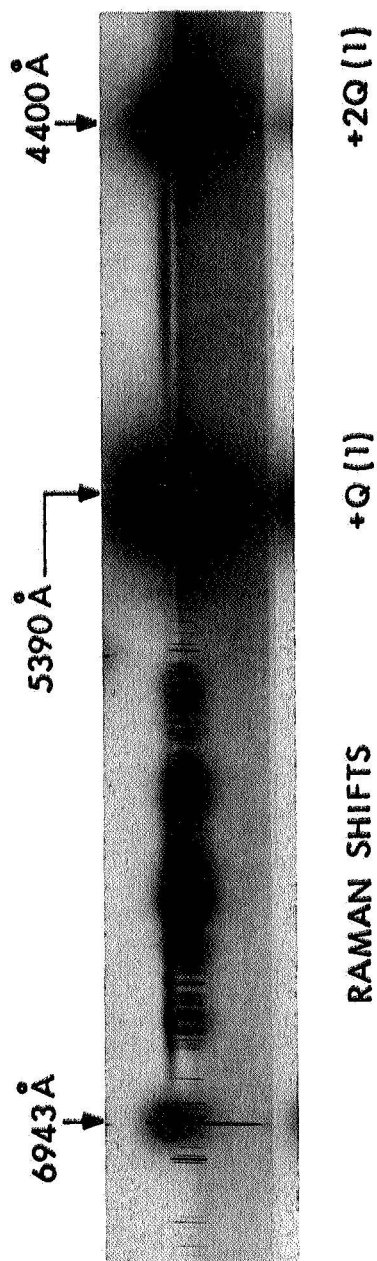


Figure 7-3. Anti-Stokes Spectrum of H_2

the chemical substances that are used as the scattering medium. Fairly complete lists of materials which can be used in SRS, and the shifts that they produce, have been recently published.¹⁷⁶ Thus, a choice from over 100 materials can be made to find one which is capable of providing Raman laser radiation at any wavelength desired for a particular application. From the point of view of ozone probes, the most useful Raman laser will be one which emits wavelengths which lie both within and outside of the absorption bands of ozone. This wavelength requirement also helps to identify the type of laser radiation that should be used as the excitation source for the SRS wavelengths, as will be discussed in the following subsection.

7.2 EXCITATION SOURCES FOR STIMULATED RAMAN SCATTERING

The phenomenon of SRS has been observed to occur only when high-intensity, giant-pulsed laser radiation is used. Thus, relatively low intensity, gas laser radiation can be excluded from consideration in any scheme involving Raman laser probes. The excitation wavelengths which have successfully been used for the production of Raman laser radiation are the primary emission wavelengths of the ruby and neodymium lasers, 6943Å and 10,580Å, respectively, and their so-called second harmonic wavelengths, 3472Å and 5290Å. The latter two wavelengths are produced by passing the primary laser radiation through a crystal which has nonlinear optical properties. The second harmonic (or frequency-doubled) radiation which emerges from the crystal is usually only of the order of a few percent as intense as that of the primary laser, although with internal modulation techniques it is possible to greatly enhance the conversion efficiency.¹⁷⁷ In any case, SRS is not as readily achieved with the second harmonic radiation as it is with the primary laser radiation, mainly because of the lower intensity available at the doubled frequency. Furthermore, complicating effects of two-photon

absorption can also inhibit SRS of laser radiation when the shorter wavelength excitation sources are used¹⁷⁸.

One of the significant findings of the experiments performed during the reporting period is that a "pseudo-SRS" spectrum of the second harmonic radiation can be readily produced, as is described in the appendix. That is, even though the mechanism which produces the spectrum is not truly SRS, coherent radiation is produced at wavelengths that would have been produced by the latter mechanism. If details of the mechanism are not considered, it can be said that the relatively low intensity and the two-photon absorption process are factors which can easily be overcome in the production of Raman laser wavelengths with the second harmonic of giant-pulsed laser radiation. This is explained more fully in the Appendix.

From a consideration of the ozone absorption bands, it is clear that a ruby laser is more suitable than a neodymium laser. The proximity of the Chappuis bands to 6943Å and of the Hartley-Huggins bands to 3472Å ensures that Raman laser radiation generated by these two wavelengths will be within the ozone absorption bands.

7.3 CHOICE OF RAMAN SCATTERING MEDIUM

For the present application, gases were considered to be the ideal scattering media for a number of reasons: (1) The largest frequency shifts in SRS are produced by gases, e.g., H_2 (4155 cm^{-1}) and CH_4 (2915 cm^{-1}). This proves to be important in Raman-shifting laser radiation from 3472Å down to the vicinity of 3000Å. (2) The efficiency of conversion into Raman shifted wavelengths is generally greater when gases are used, as compared to liquids and solids. For example, the first Stokes line of both methane and hydrogen is approximately 20% as intense as the incident laser radiation. When

liquid samples are used, typical conversion efficiencies are between 1% and 5%. (3) The fact that gases are essentially dispersionless allows most Raman frequency components to emerge from the scattering cell with essentially the same angular divergence as the excitation laser radiation. When liquid samples are used, the various anti-Stokes components emerge from the scattering cell with different angular divergences, as the result of certain momentum-matching requirements in the liquid.

The ideal Raman laser probe would appear to be one which produced stimulated Raman frequencies centered about both the 6943Å and 3472Å laser components. The former would be used in conjunction with the visible Chappuis bands and the latter with the ultraviolet Hartley-Huggins bands. The simultaneous production of SRS in gases with two different excitation wavelengths has not been previously reported. The successful generation of Raman laser radiation with 6943Å and 3472Å, as reported in the Appendix, therefore represents a new scientific accomplishment. Because of the results obtained, it can be stated that intense coherent radiation can be produced at the wavelengths listed in Table 7-1.

Any combination of these wavelengths could be used in the active Raman laser probe technique, as will be described in more detail in subsequent reports. Some wavelengths lie within the Chappuis absorption bands, others within the Hartley-Huggins bands, and others in wavelength regions which are free from ozone absorption. All of these wavelengths will be of value in atmospheric ozone measurements. It is also possible to simultaneously generate two sets of wavelengths, using a mixture of two gases, and several wavelengths which are intermediate between those produced by the individual gases¹⁷⁹. However, unless later analysis proves this to be advantageous, only single component gas scattering media will be considered for use in the active probe technique.

TABLE 7-1

RAMAN LASER WAVELENGTHS AS PRODUCED BY RUBY LASER EXCITATION
(6943Å) AND ITS SECOND HARMONIC (3472Å)

<u>Gas Medium</u>		<u>6943Å SRS Wavelengths</u>	<u>3472Å SRS Wavelengths</u>
Hydrogen	$\left\{ \begin{array}{l} S_2 \\ S_1 \\ AS_1 \\ AS_2 \end{array} \right.$	- - -	4879Å
		9760Å	4057Å
		5390Å	3033Å
		4400Å	2694Å
Methane	$\left\{ \begin{array}{l} S_2 \\ S_1 \\ AS_1 \\ AS_2 \end{array} \right.$	- - -	4352Å
		8706Å	3862Å
		5774Å	3152Å
		4940Å	2887Å
Deuterium	$\left\{ \begin{array}{l} S_2 \\ S_1 \\ AS_1 \\ AS_2 \end{array} \right.$	- - -	4382Å
		8766Å	3874Å
		5748Å	3144Å
		4904Å	2874Å

The procedure used and the results obtained in the Raman laser experiments are described in the appendix. The results have also been analyzed in an attempt to identify the nature of the interaction which produces the Raman laser frequencies. On the basis of the results obtained, the analysis presented in the appendix appears to be the correct one. However, one critical measurement which would unambiguously distinguish between the two possible mechanisms, SRS or the mechanism referred to as pseudo-SRS in the Appendix, has yet to be performed. The experiment involves a measurement of the relative intensities of the Stokes and anti-Stokes components of the scattered radiation. According to the interpretation given in the appendix, which is based on an analysis by Giordmaine¹⁸⁰, the Stokes and anti-Stokes components should be of approximately equal intensity. On the other hand, when the lines are produced by SRS, the Stokes intensity is an order of magnitude greater than the anti-Stokes intensity. Preliminary attempts to measure the relative intensities proved to be unsatisfactory. Since the efficiency of the Raman laser probe technique depends on the intensities of the Raman-shifted components, the experiments will be repeated.

The availability of high-intensity, directional Raman laser radiation at wavelengths which are pertinent to the ozone optical absorption bands opens several possibilities regarding worldwide ozone monitoring by optical means. Experimental configurations in which Raman lasers could be employed include those in which the laser is flown in a satellite and detectors placed in another satellite or at ground stations. The attenuation of the different wavelength components would serve as a measure of the ozone content between the laser emitter and the detectors. The backscattering of Raman laser radiation by the atmosphere could also be examined by placing detectors aboard the same satellite as the Raman laser. However,

the simplest and probably the most reliable use of Raman lasers for atmospheric ozone measuring appears to be one in which Raman laser radiation is transmitted from ground stations to an orbiting satellite aboard which several photomultiplier tube detectors are placed. Figure 7-4 illustrates the geometry involved.

Calculations designed to show that the Raman intensities are readily detectable are presented in the following subsection, where the specific examples of 3472Å and 3034Å are used. For these calculations, intensities of the emitted radiation were used which are typical of those measured in the experiments described in the appendix. In subsequent reports the limits of accuracy of this proposed technique will be established and a survey of recent developments in Raman laser technology will be given to show that the intensities can be considerably enhanced.

7.4 ACTIVE PROBE SIGNAL INTENSITY

This subsection describes the calculation of the number of signal photons received when an actual system employing a Raman-shifted frequency-doubled ground-based laser is used as described in the preceding subsection. The geometry associated with such a system is shown in Fig. 7-4. The area A subtended by the laser beam of divergence and at a slant range R is given as

$$A = \frac{\alpha R^2 \pi}{4} \quad (7-1)$$

As a result, the incident signal power P_I on a detector of area a in a system employing a laser of power P_R is given as

$$P_I = \frac{P_R^4 a t}{\alpha R^2 \pi} \quad (7-2)$$

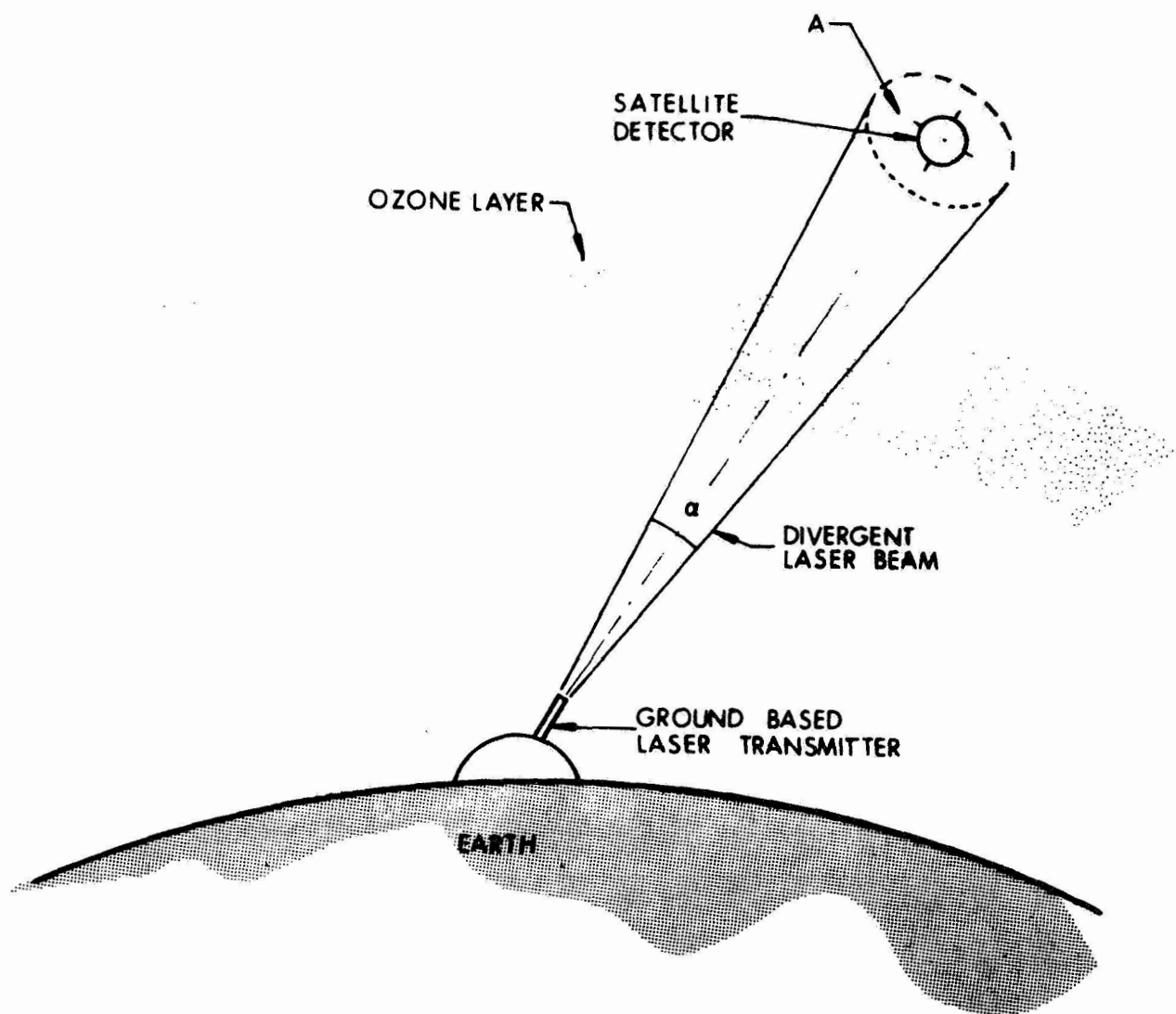


Figure 7-4. Geometry of Ground-Based Laser with Orbiting Detector

where t is the atmospheric transmission at the wavelength of the laser radiation, and a is the detector aperture.

Figure 7-5 shows slant ranges as a function of zenith angle for a 1000km orbit. The atmospheric transmission for light at several laser wavelengths of interest were determined by considering clear air atmospheric scattering and ozone absorption as a function of zenith angle.

The actual detected signal power P_D is given by

$$P_D = P_I E q \quad (7-3)$$

where E is the optical efficiency of the detector system and q is the quantum efficiency of the phosphor.

Calculations were performed to determine the number of detected photons for a system in which

$$a = 6 \text{ in.}^2$$

$$E = 0.9$$

$$q = 0.12 \text{ at } 3472\text{\AA}$$

$$P_R = 0.5 \text{ megawatt at } 3472\text{\AA}$$

The results of this calculation are shown in Table 7-2.

Similar calculations were performed for a system radiating at 3034 $\text{\AA}$ and using vertical ozone contents which differed by a factor of three. The results of the calculations are summarized in Fig. 7-6.

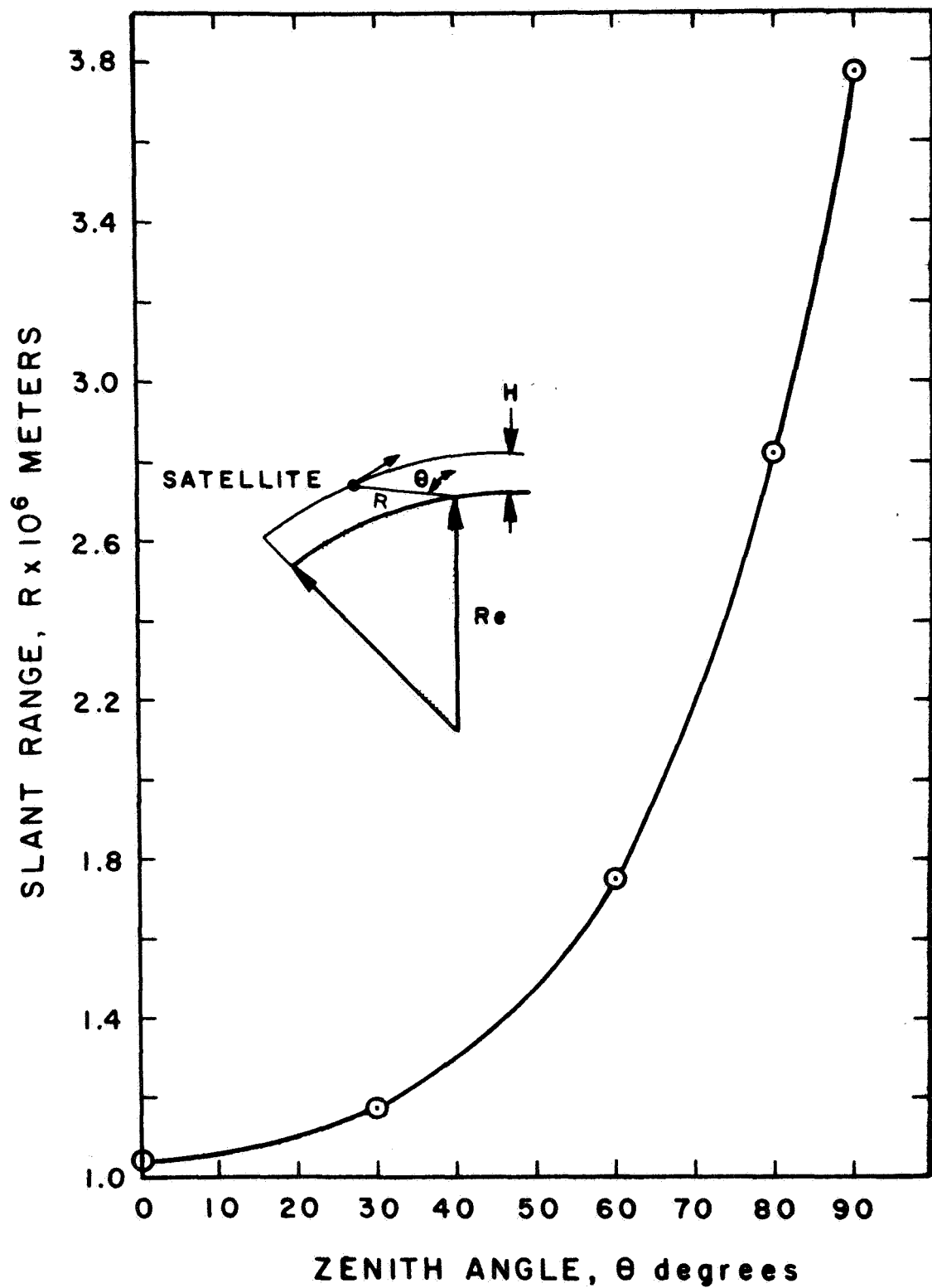


Figure 7-5. Slant Range versus Zenith Angle for 1000 km Orbit

TABLE 7-2

SIGNAL INTENSITY FOR VARYING ZENITH ANGLE

<u>θ = Zenith Angle</u>	<u>Range</u>	<u>Signal Photoelectrons/ Pulse At 3472Å</u>
0°	1×10^6 m	2.24×10^9
10°	1.04×10^6 m	2.07×10^9
20°	1.10×10^6 m	1.86×10^9
30°	1.18×10^6 m	1.44×10^9
40°	1.30×10^6 m	1.06×10^9
50°	1.46×10^6 m	0.74×10^9
60°	1.74×10^6 m	0.45×10^9
70°	2.14×10^6 m	0.25×10^9
80°	2.80×10^6 m	0.03×10^9
90°	--	--

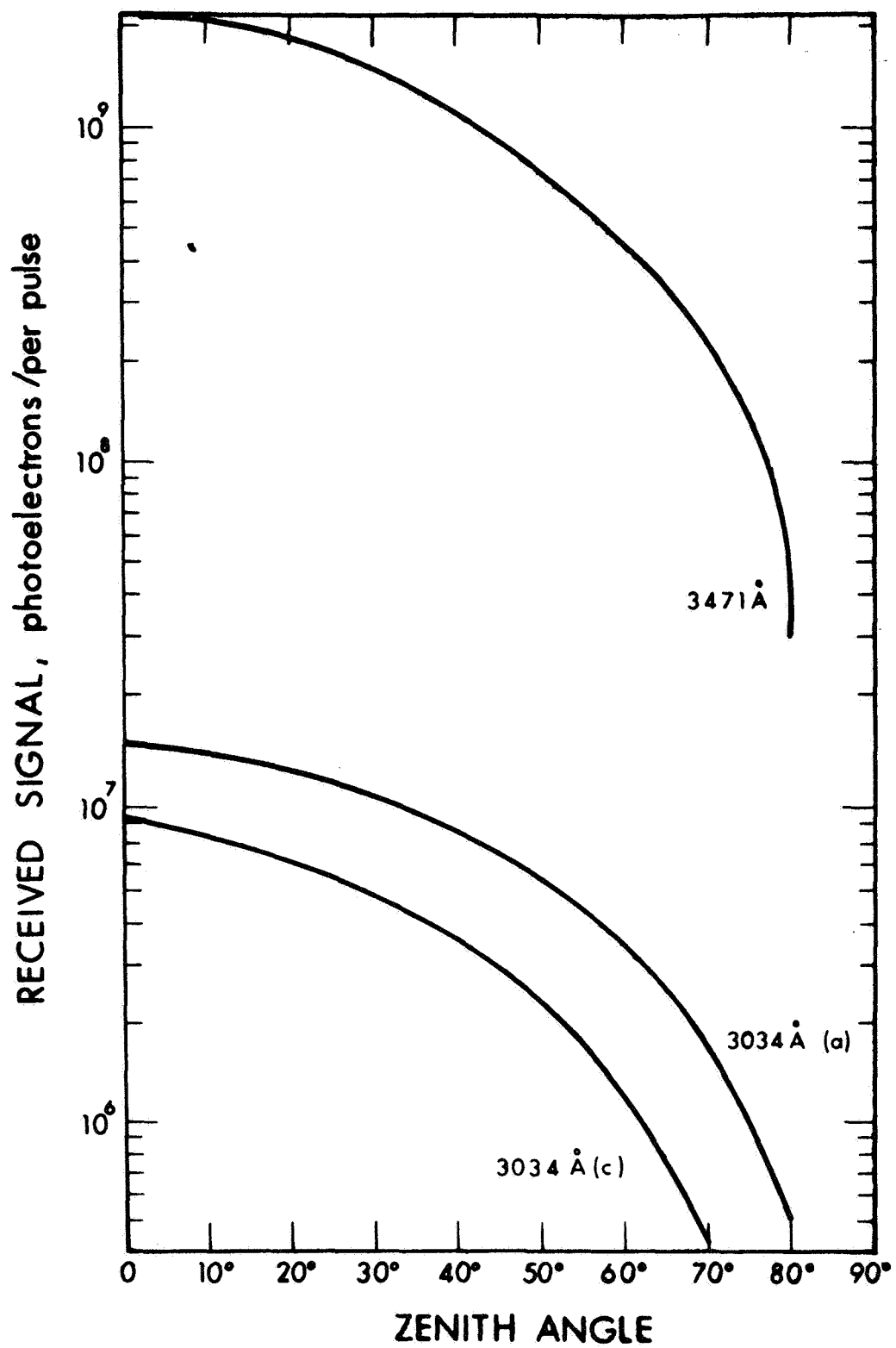


Figure 7-6. Received Signal versus Zenith Angle

The calculations were performed for the purpose of demonstrating the detectability of the Raman laser radiation as transmitted to a satellite through various atmospheric slant paths. The results show that the received signal is well above the noise level of the detector system, including background radiation. Similar calculations for the other wavelengths shown in Table 7-1 will be performed during the next year, and the limits of the accuracy with which the atmospheric ozone can be measured will be established. For the present, it should be pointed out that the technique under evaluation would be especially valuable for determining variations in the horizontal distribution of ozone. If used in conjunction with a technique which measures the vertical distribution with high accuracy, the distribution of atmospheric ozone over large geographical areas could be well mapped from a single satellite.

SECTION 8

CONCLUSIONS

The work performed during the period covered by this interim report consisted in large part of a compilation and examination of the vast amount of literature that has been published on the spectroscopy of ozone, the measurement of its atmospheric concentrations by optical means, its role in atmospheric dynamics, and its potential use as a tracer for atmospheric winds. Guided by the information derived from this literature, two ozone measuring techniques have been selected as the most promising, from among the various optical techniques, for use in conjunction with an orbiting satellite. These are: (1) the passive technique which utilizes solar radiation, as described in Section 6, and (2) the active probe method utilizing Raman laser radiation, as described in Section 7. The former offers great advantages in terms of determining vertical ozone distributions on a worldwide basis and the latter technique appears to be especially promising for measuring the total ozone content. The analyses performed, some of which were based on laboratory measurements, confirmed the practicality and reliability of the selected methods.

On the basis of well developed theories, which suffer only from a lack of supporting observational data for practical implementation, the monitoring of ozone distributions promises to be a unique and invaluable means of defining and predicting atmospheric circulations and other meteorological behavior.

The approach most likely to yield significant information on the motion of ozone on a global scale is to map the vertical ozone distribution, or ozone profile, at numerous geographical locations and to continuously monitor this information as the satellite orbits around the earth.

8.1 ADVANTAGES OFFERED BY OPTICAL MEASURING TECHNIQUES

During the course of program effort, and as detailed in this report, a number of distinct advantages of using radiation in the optical regime for ozone atmospheric measurements became apparent. These are listed in the following subsections.

8.1.1 ACCURACY OF OZONE ABSORPTION COEFFICIENTS

Ozone molecule exhibits broad absorption bands in the infrared, visible and near UV, whose coefficients have been carefully measured by many workers. The measurements have been independently repeated, compared and refined. They have been critically evaluated in connection with meteorological applications. There exists a general agreement as to the most reliable set of values, and the coefficients are now considered to be known to a high degree of precision.

8.1.2 RANGE OF VALUES OF OPTICAL ABSORPTION COEFFICIENTS

Large differences exist in the absolute magnitudes of ozone cross-sections at visible and UV wavelengths ($\sigma \sim 10^{-21} \text{ cm}^2$ at $4800\text{\AA}$, $\sigma \sim 10^{-17} \text{ cm}^2$ at $2600\text{\AA}$.) This means, in effect, that variations of over four orders of magnitude in the total ozone content in an optical path can be measured by absorption measurements. This range also insures that:

- a. Ozone concentrations at altitudes as high as 75-80 km can be measured from a satellite by using the larger cross-section values.
- b. Solar radiation which traverses the layer of maximum ozone concentration will emerge with an attenuation that can accurately be measured by using the smaller cross-section values.

8.1.3 METEOROLOGICAL APPLICATION OF OZONE ABSORPTION SPECTROSCOPY

Optical techniques have been used to measure atmospheric ozone content for over 45 years. All of the information we now possess concerning atmospheric ozone was first obtained by optical means (total ozone content, its vertical distribution, variations in these latter two quantities, and, in fact, the very existence and the approximate height of the ozone layer were first determined through optical spectroscopic measurements.) The history of ozone spectroscopy and measurements of its atmospheric content are, in fact, inseparable. The physics and optical principles involved in optical ozone measurements have been well developed and analyzed, corrections have been introduced, and the principles are thus well understood. Measurements from a satellite would not involve any radical or revolutionary concepts, but rather an adaptation or modification of some well-established technique. Satellite measurements do, however, offer the promise of greater accuracy and precision in ozone measurements by optical methods, as well as global coverage on a continuous basis.

8.1.4 SOLAR RADIATION AS A SOURCE FOR ABSORPTION MEASUREMENTS

The solar emission spectrum possesses a broad maximum in the visible and near UV and IR spectral region and thus constitutes a very strong source of radiation which can be used in atmospheric ozone absorption measurements. The solar radiation is so intense that

narrow wavelength intervals can be taken, high spatial resolution optics can be incorporated into the optical system, and yet very large signal-to-noise ratios will be obtained by photomultiplier tube detectors.

8.1.5 LASERS AS SOURCES FOR ABSORPTION MEASUREMENTS

Since discrete wavelengths of radiation are generally used to measure atmospheric ozone (even when the sun is used as a source) recently developed sources of intense, collimated, monochromatic radiation (Raman lasers) can be employed as sources for absorption measurements. Significant progress has recently been made at EOS in the understanding of the physics involved in the production of visible and near UV Raman laser radiation. (See Appendix and references cited therein.) The availability of intense radiation at desired wavelengths for ozone determination opens new possibilities with respect to the relative positioning of the emission source and the detectors used for measuring the radiation which is attenuated by the atmospheric ozone.

SECTION 9

BIBLIOGRAPHY AND REFERENCES

This section contains a compilation of references to literature articles which pertain to the topics discussed in Phase I of this report. The references are grouped into categories depending upon whether the main emphasis is on ozone photochemistry, meteorological significance, spectroscopy, etc. However, the classification of the articles under one heading is somewhat arbitrary, since most of the articles deal with more than one of the above topics. It is to be noted that not all literature references appearing in this bibliography have been cited in the text of this report. For convenience, references which have been cited are collected in Subsection 9.6, "Cited References."

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APPENDIX

The phenomenon of stimulated Raman scattering (SRS) can potentially be used to great advantage in molecular spectroscopy investigations, since it results in the production of pulsed, intense, coherent, collimated, and monochromatic radiation. In most instances, SRS has been produced by using either 6943Å ruby laser or 1.058μ neodymium laser radiation. On the other hand, the so-called second harmonic radiation of these laser sources, at 3472Å and 5290Å, respectively, would provide a more useful set of discrete SRS wavelengths, i.e., "laser-like" radiation in the ultraviolet spectral region where the electronic absorption bands of a great number of molecules are located. However, few experiments of SRS involving the second-harmonic of giant-pulsed laser radiation have been reported. One reason for this is that the powers available at the second harmonic wavelength are an order of magnitude or two lower than those of the primary laser radiation. In certain cases, quenching processes, such as two-photon absorption, may also serve to inhibit SRS of the second harmonic radiation.

This appendix describes experiments which demonstrate that when ruby laser radiation (6943Å) and its second harmonic (3472Å) are simultaneously passed through an SRS active material, a "pseudo-SRS" spectrum of the 3472Å radiation can be produced. That is, coherent radiation is made to appear at wavelengths identical to those which would be produced by SRS of the 3472Å radiation.

However, power measurements indicate that the mechanism responsible for the interaction is more properly described as a modulation of the $3472\text{\AA}$ radiation by molecular vibrations which are coherently driven by the $6943\text{\AA}$ laser radiation. The effect is similar to that which has been shown to account for the Raman-type scattering of a probe light by coherently driven lattice vibrations¹. In the present case, the effect was used to produce second harmonic pseudo-SRS spectra of hydrogen and methane gases and of a number of liquid substances.

The experimental arrangement is as shown in Fig. A-1. The ruby laser was Q-switched by means of a rotating prism and produced between 40 and 90 megawatts of $6943\text{\AA}$ radiation during a 34-nanosecond pulse. The $3472\text{\AA}$ radiation was produced by passing the ruby laser radiation through a 2.5 cm KDP crystal whose z-axis was oriented so as to allow the production of $3472\text{\AA}$ through a nonlinear polarization, phase-matching mechanism². The power and energy measuring devices shown in the figure were used to monitor the intensities of the $6943\text{\AA}$ and $3472\text{\AA}$ radiation components incident on the scattering medium. A variety of filters were used to differentially attenuate the two radiation components before they entered the scattering medium in order to determine the intensity combinations which produced second harmonic SRS spectra. The occurrence or nonoccurrence of SRS was determined spectrographically, by means of an f/6.3, 0.75m Jarrell-Ash spectrograph. The discussion below will deal only with the results obtained for the specific example of hydrogen gas.

The threshold power for SRS of laser radiation by hydrogen gas is determined by such factors as gas pressure and temperature³, the effective focal volume of the lens system used⁴, and the linewidth and polarization of the incident laser radiation^{5,6}. With the

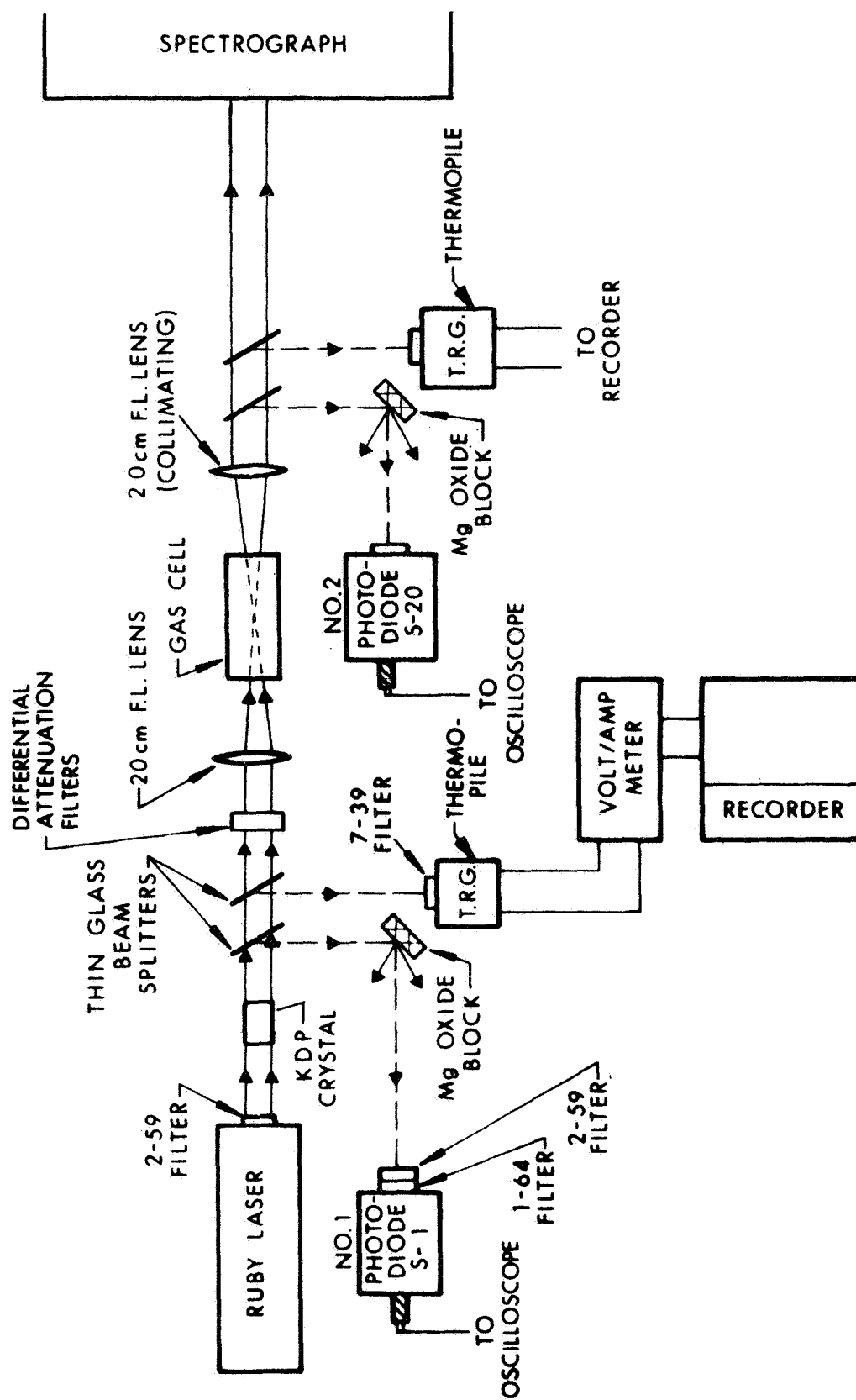


Figure A-1. Experimental Arrangement used in the Determination of Threshold Values for SRS of 6943 Å and 3472 Å Laser Radiation

coherent radiation can be caused to occur at $\nu' \pm n\nu_R$, where ν_R is the Raman shift characteristic of the scattering material. This technique was also used to produce pseudo-SRS spectra of methane and of carbon disulfide, benzene and ethyl iodide. Experiments, which will be described elsewhere, show that ν' need not necessarily be the second harmonic of incident laser radiation, but may also be the anti-Stokes SRS component of a preliminary scattering material, i.e., when two scattering media are used in tandem.⁷

The mechanism responsible for the effect referred to herein as pseudo-SRS is a general one and was first described in terms of classical scattering theory by Garmire,⁴ et al, to account for the production of multiple vibrational frequency shifts in SRS. Since then, extensions of the theory have been used to explain: (1) the detection of laser-stimulated lattice vibrations, or optical phonons, by low-intensity monochromatic probes;¹ (2) the appearance of combination (sum and difference) vibrational Raman shifts in the SRS spectra of two gases, which may either be two components in a gas mixture or different gases in separate cells³; and (3) the production of a complex vibrational-rotational SRS spectrum of hydrogen when excited by giant-pulsed 1.058 μ laser radiation⁸.

Since the hydrogen gas can be considered to be essentially dispersionless, a simplified form of the theory, which neglects momentum-matching requirements, can be used in the present case. The frequencies emitted by the hydrogen gas can then be deduced by analyzing the time-dependence of the oscillating electric dipole moment associated with coherently driven molecular vibrations. This dipole moment, $\vec{\mu}$, is given by

$$\vec{\mu} = q \left(\frac{\delta \alpha}{\delta q} \right)_0 \vec{E} \quad (1)$$

hydrogen gas at 40 atmospheres and at room temperature, and with the experimental arrangement shown in Fig. A-1, the threshold power for SRS of $6943\text{\AA}$ was determined to be $30\text{ MW} \pm 3\text{ MW}$. This threshold value was obtained whether or not the $3472\text{\AA}$ radiation was simultaneously passed through the hydrogen sample. The onset of $6943\text{\AA}$ SRS was determined by the appearance of spectral lines at the frequencies $\nu_L \pm n\nu_{H_2}$, where ν_L is the laser frequency, $14,400\text{ cm}^{-1}$, $\nu_{H_2} = 4155\text{ cm}^{-1}$ and $n = 0, 1, 2, \dots$. The maximum intensity of $3472\text{\AA}$ produced by the KDP crystal was 1 megawatt. It was not found possible to excite an SRS spectrum with this second harmonic radiation, as long as the intensity of $6943\text{\AA}$ radiation simultaneously incident on the hydrogen sample was kept lower than 30 MW by differential filtering. That is, the powers available at the second harmonic wavelength were clearly below the threshold power required for the production of SRS. (The actual threshold for $3472\text{\AA}$ SRS was not determined, due to the limited second harmonic generation efficiency attained in the experiments described here.)

However, even though the $3472\text{\AA}$ intensity was below the SRS threshold, the second harmonic SRS frequencies, $2\nu_L \pm n\nu_{H_2}$, appeared in the spectrum whenever the incident $6943\text{\AA}$ radiation² was sufficiently intense to produce the primary SRS frequencies, $\nu_L \pm n\nu_{H_2}$. That is, once the $6943\text{\AA}$ SRS threshold was exceeded, the $3472\text{\AA}$ ² SRS also occurred simultaneously, with no apparent additional threshold requirement. The pseudo-SRS spectrum was observed when powers as low as 0.2 megawatt of $3472\text{\AA}$ radiation were used, providing that more than 30 megawatts of $6943\text{\AA}$ were simultaneously incident on the sample.

The results described above are taken as evidence that if relatively low intensity radiation of frequency ν' is transmitted through a medium in which SRS is excited by high intensity laser radiation,

where q is the amplitude of the molecular vibration which is driven by a force which is proportional to the square of the total electric field^{3,4}, and $(\frac{\delta\alpha}{\delta q})_0$ is the polarizability derivative with respect to q , which is assumed to be isotropic for simplicity. It has been shown³ that with the gas pressures used, in the present experiments the driving force is due primarily to the electric field components associated with the high-intensity laser radiation (6943Å) and its Raman-shifted frequencies. When the time dependence of q and the components of $\vec{E}$ are explicitly inserted into Eq. 1, it is readily seen that if there is a component of the field corresponding to the frequency ν' , the frequencies $\nu' \pm n\nu_R$ will be emitted by the oscillating dipole, provided that the frequencies ν_R are excited in SRS by the ruby laser.

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SECTION 1

INTRODUCTION

The present report represents a summary of a two-year study and research effort, the goal of which was to evaluate optical methods of monitoring the atmospheric ozone content on a continuous basis and on a worldwide scale from an orbiting satellite. The ozone monitoring methods were to be evaluated on the basis of their ability to provide information relative to the tracing of large scale atmospheric air mass motions, such as from the equator to the poles. The first interim report dealt with: (a) a compilation of references to numerous literature articles dealing with the complex interrelationships between atmospheric ozone content and distribution, on the one hand, and the temperature and wind fields of the upper atmosphere, on the other. The unanimous opinion stated in these articles was that continuous observational data on the worldwide ozone distributions could lead to an analytical description of these relationships. Further monitoring of these distributions could then be of prognostic value as far as global circulation patterns are concerned; (b) a survey of the available literature concerning the spectral absorption properties of ozone in the infrared, visible and ultraviolet regions. The conclusion arrived at in this survey was that the optical absorption coefficients of ozone, having been measured by dozens of investigators, are known to a high degree of precision and can be used with confidence in quantitative absorption determinations of ozone content; (c) reports of experiments with Q-switched lasers which resulted in the production of stimulated Raman emission at various wavelengths in the visible, ultraviolet and near infrared. The purpose of these experiments was to demonstrate that intense Raman laser radiation could be generated at wavelengths corresponding to ozone absorption bands, and could thus be incorporated into remote ozone probing schemes; (d) an ozone monitoring scheme utilizing solar radiation which appears to be

ideal for measuring high-resolution vertical profiles of atmospheric ozone from satellites. The technique, known as the occultation method, depends on measuring the intensity of solar radiation as it passes through the earth's atmosphere on a near tangential path. The optical and physical principles of the technique were described in detail without reference, however, to a specific satellite as a vehicle for the measurement. No attempt was made in the first interim report to describe an instrument design or to demonstrate the feasibility of the technique from an engineering standpoint.

The present report deals in large part with a description of the occultation measurement, as it would be performed on a sun-synchronous, polar orbiting satellite. This particular type of satellite was chosen as a vehicle for the experiment since: (a) an analysis showed that the orbital parameters of this type of satellite, of which the Nimbus meteorological satellite is a specific example, are ideal for continuous monitoring of the vertical ozone distributions at high latitudes; and (b) consultation with UCLA meteorologists* disclosed that the ozone data obtained from the high-latitude coverage provided by Nimbus satellites represents the type of information that is needed to unravel the role that ozone plays in the large scale polar atmospheric circulation patterns. Detailed analyses were performed which treated the interrelationships among the optical, mechanical, detector, and electronic components of the instrument, as well as the instrument/satellite interface aspects. The results of the design study demonstrated the feasibility and practicality of a Nimbus ozone measuring instrument. A proposal was accordingly submitted to the National Aeronautics and Space

*The author of this report gratefully acknowledges numerous helpful discussions during the program effort with Dr. C. E. Palmer of the Institute of Geophysics and Planetary Physics, UCLA, and Dr. S. V. Venkateswaran of the Department of Meteorology, UCLA. Several of the discussions appearing in Section 3 of this report were kindly contributed by Professors Palmer and Venkateswaran.

Administration for the inclusion of the occultation measurement as part of the flight package on the Nimbus E and F satellites scheduled to be launched in the early 1970's.

Since an occultation measurement from a satellite of the Nimbus type was identified as the most promising and useful method for upper atmospheric ozone measurements, a major emphasis was placed on analyzing and developing the details of this technique during the contract effort. Probing concepts utilizing laser radiation, which were discussed in the first Interim Report, were therefore investigated at a reduced level of effort during the second year of the contract. A ground-based laser probe concept, which appears to offer promise as a means of measuring ozone in the lower atmosphere, is discussed in Section 2.

In addition to the results reported here, considerable effort has been devoted to the preparation of three publications which, in large part, summarize the results and conclusions of this program. These publications are:

- a. "Some New Aspects in Stimulated Raman Scattering from Hydrogen Gas," by J. Duardo, F. M. Johnson, and L. J. Nugent, IEEE, J. Quant. Electronics, June 1968.
- b. "The Use of Nimbus Satellites for Measurements of Atmospheric Ozone over Polar Areas," by J. Duardo, R. E. Hill, C. E. Palmer, and S. V. Venkateswaran, presented at the 14th Annual Meeting of the AAS, Dedham, Mass., 14 May 1968.
- c. "Critique of Paper entitled 'Some Aspects of Remote Atmospheric Sensing by Laser Radar' by R. M. Schotland," by J. Duardo. Critique delivered at the National Academy of Sciences - Committee of Atmospheric Sciences Remote Atmospheric Probing Panel, Chicago, 18 April 1968, and will be published in the panel proceedings.

SECTION 2

ATMOSPHERIC OZONE MEASUREMENTS USING LASERS

Several conceptual methods of measuring atmospheric ozone content through the use of lasers were examined. These included configurations in which a laser transmitter and a detector were satellite-mounted, either in the same satellite or in separate satellites. Also considered were configurations involving a ground-based laser transmitter and a satellite-based detector, and vice-versa. Consideration in each case was given to the wavelength region in which the system would operate. The wavelength considerations included atmospheric transmission, ozone absorption properties, and the availability of laser radiation at the wavelengths in question. These factors in turn determined the practicality of the various methods.

In evaluating laser techniques primary emphasis was placed on (a) the feasibility of the method and (b) its value, from a meteorological point of view. In connection with this latter point, the author was privileged to attend a specially convoked panel of the National Academy of Sciences in Chicago during the week of April 15-19, 1968. The purpose of the NAS-Committee of Atmospheric Sciences panel was to perform a review of existing and proposed techniques of remote atmospheric probing and to recommend areas of related research which should be supported on a national level. The author feels that the panel discussions helped define meteorological problem areas and provided a valuable insight into the types of remote measurements that would best serve the present needs of the meteorological community. The panel discussions confirmed a previously held opinion that ground-based measurements represent the most realistic application for lasers in atmospheric probing in the near future. The information obtained would pertain to the lower atmosphere,

where satellite measurements, in general, do not yield reliable data, and would be of particular value in the analysis of urban air pollution problems. While satellite-based laser techniques can be conceived which would yield useful data on the upper atmosphere, it is felt that these cannot be implemented until ground-based versions have been developed and the required instrumentation perfected. Furthermore, it does not appear at present that satellite-based laser techniques would offer any advantages over techniques utilizing solar radiation which are currently under development or have been proposed.

In the following section a concept for monitoring the ozone content of the lower atmosphere with lasers is described. The technique has not been analyzed in detail and is presented here only in outline form with the recommendation that the performance capabilities of the technique be further investigated.

2.1 ATMOSPHERIC OZONE MEASUREMENTS BY DIFFERENTIAL ABSORPTION OF BACKSCATTERED LASER RADIATION

The underlying principal for the concept discussed below is that ozone in a given atmospheric path can be measured by two-wavelength spectroscopy. That is, if the transmission through the atmosphere can simultaneously be measured at two wavelengths, one within an ozone absorption band and the other outside of the band, a measure of the ozone content can be obtained from the relative attenuation at the two wavelengths. This is true only if the wavelength dependence of atmospheric attenuating mechanisms other than ozone absorption is known or can be measured, and if the ozone absorption coefficients are known. The last condition can be considered to be satisfied since ozone absorption coefficients in the UV, visible and near IR have been measured in the laboratory under a wide range of conditions.

The first condition, i.e., a knowledge of the wavelength dependence of other attenuation mechanism, warrants some consideration. If the attenuation were due mainly to Rayleigh scattering, then either the λ^4 dependence of the scattering efficiency could be invoked or use could be made of tabulated Rayleigh scattering coefficients for air*. However, in the lower atmosphere, scattering by particulate matter is an order of magnitude more important than Rayleigh scattering by air molecules. The wavelength dependence in this case will not be the same under all circumstances, since it depends on the size distribution of the aerosol particles. Two alternatives exist: (1) a representative size distribution of particles can be assumed in all cases with a "standard" spectral scattering efficiency curve** or, (2) the wavelength dependence can be determined empirically by using two wavelengths which fall outside of the absorption band and extrapolating to a third wavelength falling inside the absorption band. On the other hand, if the laser ozone probe wavelength coincides with the 9.6μ absorption band, the λ^4 dependence may be used since the aerosol particles will be in the Rayleigh range. In any case, it appears that the contribution to the attenuation made by the Rayleigh and aerosol scatterers can be accounted for, and the resultant attenuation due to ozone absorption deduced from a two- (or three-) wavelength transmission measurement.

The method of obtaining the ozone content from a transmission measurement at two wavelengths can be shown analytically as follows: Let λ_1 be a wavelength which lies within an ozone absorption band, and λ_2 a wavelength outside of the absorption band but reasonably close to λ_1 . The transmission values for the atmospheric path in question can be written as

$$T(\lambda_1) = \exp - [\tau_1(O_3) + \tau(\text{air}) + \tau_1(\text{aerosol})] \quad (2-1)$$

* R. Penndorf, J. Opt. Soc. Am. 47, 176 (1957)

** P. T. Vanderhei, and B. J. Taylor, G.R.D. Research Notes No. 46, G.R.D., Bedford, Massachusetts.

$$T(\lambda_2) = \exp - [\tau_2(\text{air}) + \tau_2(\text{aerosol})] \quad (2-1a)$$

where τ is the contribution to the optical thickness due to the indicated types of molecules or particles at the wavelengths designated by the subscripts. Since it is assumed that the variation of the optical thickness due to air and aerosol scattering is known or can be measured,

$$\tau_1(\text{air}) + \tau_1(\text{aerosol}) / \tau_2(\text{air}) + \tau_2(\text{aerosol}) = C_2 \quad (2-2)$$

i.e., C_2 is a weighting factor which allows the optical thickness at a given wavelength to be deduced from a measured optical thickness at another wavelength.

$T(\lambda_1)$ and $T(\lambda_2)$ represent measured quantities and their ratio is then

$$T(\lambda_1) / T(\lambda_2) = \exp - [\tau_1(O_3) - C_1] \quad (2-3)$$

where

$$C_1 = [\tau_1(\text{air}) + \tau_1(\text{aerosol})] (1 - C_2) \quad (2-4)$$

The number of ozone molecules in the atmospheric path, $n(O_3)$, can then be obtained from Eq. 2-3, through the relationship

$$\tau_1(O_3) = n(O_3) \sigma(\lambda_1) \quad (2-5)$$

where $\sigma(\lambda_1)$ is the known ozone absorption cross section per molecule at the wavelength which lies within an absorption band.

2.2 ATMOSPHERIC TRANSMISSION MEASUREMENTS WITH PULSED LASERS

The above discussion has dealt only with the method of obtaining ozone concentrations by differential absorption spectroscopy, with no reference to the manner in which the transmission is to be measured. The method proposed here is that which has been developed by Sandford* in connection with laser atmospheric scatter measurements. Basically the technique depends on measuring the return signal due to backscattering of laser radiation by air and aerosol particles at a given height in the atmosphere. Height (or altitude) discrimination in the return signal can be obtained by time-gating the detector with respect to the optical pulse emission from the laser. The basic geometry of the technique is illustrated in Fig. 2-1.

Two assumptions are essential to the measurement of atmospheric transmission by this technique: (1) the atmosphere between the laser probe and the altitude (h) to which the transmission is to be measured is horizontally uniform. (2) The laser radiation is isotropically scattered by the volume element of atmosphere located at the altitude (h). When these two assumptions are valid, the atmospheric transmission is determined by measuring the contribution to the return signal that originates at the altitude (h). This is done for a series of elevation angles, σ , of the laser transmitter. For a detector with fixed collecting aperture area, A, the fraction of the total radiation that is scattered into the detector solid angle is given by

$$\Delta I_s(h) / I_s(h) = \frac{1}{4\pi} \frac{A}{\ell^2} = \frac{1}{4\pi} \frac{A}{h^2 \csc^2 \sigma} \quad (2-6)$$

where ℓ is the slant distance to the volume element located at the altitude (h). For a horizontally uniform atmosphere the transmission

*M.C.W. Sandford, J. Atm. Terr. Phys. 29, 1657 (1967)

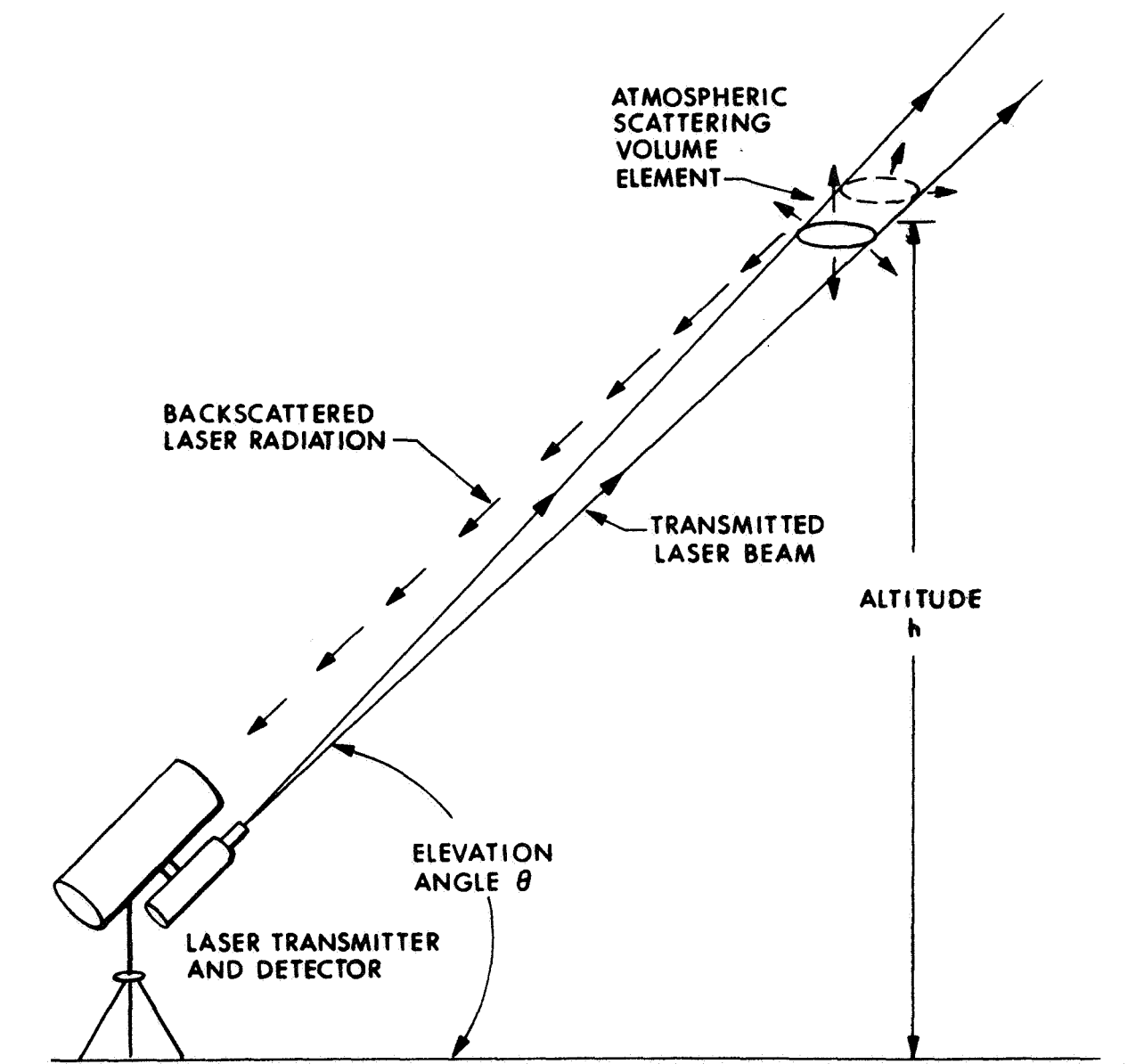


Figure 2-1. Schematic Illustration of Atmospheric Transmission Measurements by a Laser Pulse

for a slant path, T_s , is related to the vertical transmission T_v , through the relationship.

$$T_s(h) = \exp[-\tau_v(h) \csc \theta] = T_v^{(h)} \exp[\csc \theta] \quad (2-7)$$

where $\tau_v(h)$ is the vertical optical thickness of the atmosphere between ground level and (h) . By combining Eqs. 2-6 and 2-7, and allowing for a two-way path, the following expression is obtained for the ratio of laser radiation received by the detector to the transmitted radiation.

$$I_R(h) / I_o \times \csc^{-2} \theta T_v \exp[2 \csc \theta] \quad (2-8)$$

or

$$\log [I_R(h, \nu) / I_o] = k - 2 \log \csc \theta + 2 \csc \theta \log T_v \quad (2-9)$$

In the above equation, k is a factor that depends on instrumental parameters and on the atmosphere, but is independent of θ .

The left hand side of Eq. 2-9 represents a measured quantity, i.e., the ratio of received return power to transmitted power when the laser elevation angle is σ . If a series of readings over a range of ν values are performed, the T_v values can be deduced from a plot of the quantity

$$\{ \log [I_R^{(h, \nu)} / I_o] + 2 \log \csc \theta - k \} \text{ versus } 2 \csc \theta. \quad (2-10)$$

2.3 CONCLUSIONS AND RECOMMENDATIONS

Atmospheric transmission at the ruby laser wavelength has been measured in the manner described above by Sandford with satisfactory results. His transmission measurements relate to an atmospheric path from ground level

to an altitude of 6 km. It would appear, nevertheless, that the method requires considerably more analysis before it can be successfully implemented as an ozone probe. In particular, it appears that the angular dependence as expressed by Eq. 2-8 is over-simplified. The angular dependence of the scattering function of typical air and aerosol mixtures should be analyzed in detail over the anticipated range of elevation angles and for the transmitted wavelengths. Also, the lasers that would be used for the transmission measurements were not specified in the discussion above. This can be done only after a more detailed analysis is possible, which would include signal-to-noise calculations to indicate the altitude capabilities of the proposed lasers, and the ozone absorption strengths at the laser wavelengths and over the corresponding paths through the atmosphere, etc.

Among the possibilities are CO₂ lasers whose output wavelengths fall within and in the vicinity of the 9.6 μ absorption band, and Raman lasers whose wavelengths coincide with the visible and UV absorption bands. Specific examples of these lasers have been discussed in detail in previous reports.

The assumption of a horizontally uniform atmosphere should also be examined carefully. Further analysis may show that this is unnecessary, since it is possible to obtain continuous recordings of laser return as a function of altitude. The transmission values for a continuous number of altitudes and a set of angles can thus be measured and non-uniformities in transmission detected. Such nonuniformities might be due to patchiness in the ozone distribution, for example. Although many of the details of the techniques described here remain to be analyzed, the principles upon which it is based appear to be valid and straightforward. The concept discussed above appears to warrant further examination, especially since the need for measuring ozone in the lower atmosphere is becoming increasingly urgent in the analysis and control of air pollution.

SECTION 3

PROPOSED METHOD OF UPPER ATMOSPHERIC OZONE MONITORING FROM NIMBUS-TYPE SATELLITES

This section is based on a proposal which was made to NASA, through their respective organizations, by three coinvestigators: J. A. Duardo of Electro-Optical Systems, Inc.; C. E. Palmer, Institute of Geophysics and Planetary Physics at UCLA; and V. S. Venkateswaran, Department of Meteorology at UCLA. It is divided into two parts: Part I describes the scientific aspects of the investigation, and Part II describes the engineering necessary for its success.

The intention of the proposed endeavor would be to measure atmospheric ozone by monitoring the attenuated solar radiation in the middle ultraviolet as the sun is occulted by the earth and its atmosphere. The monitoring would be performed in ten different wavelengths by a spectrometer viewing a narrow slice of the solar image from the satellite, Nimbus E. The measurements are capable of yielding ozone distributions at high latitudes, between 65 and 80° (N or S) and at intervals of 30° longitude during successive orbits. By careful treatment of the data, the vertical ozone profiles can be obtained with good height resolution between 20 and 70 km.

The ozone information obtained in this manner would be a valuable aid in the analysis of the buildup and collapse of the polar stratospheric vortex. The collapse of the vortex is a dramatically abrupt meteorological phenomenon whose exact time of occurrence is highly variable. The collapse is known to be associated with large-scale changes of air circulation in both the stratosphere and mesosphere. The aeronomic and ionospheric phenomena which accompany it remain obscure; success of the project would, at least, illuminate the aeronomic problem. Beyond

this lies a much more important scientific objective--the acquisition of data for one year and for both polar caps. which will be the base of a new ozone climatology in high latitudes.

3.1 POLAR VORTEX BREAKDOWN AND SUDDEN STRATOSPHERIC WARMING

A meteorological phenomenon in which ozone is believed to play an important role is commonly referred to as the collapse or "breakdown" of the polar vortex. This phenomenon is related to the large-scale polar atmospheric circulation pattern and has been the subject of many meteorological investigations in recent years.

The circulation of the polar atmospheres above 12 km differs in a remarkable way from that at lower altitudes. In both hemispheres, the autumn and early-winter circulation of the lower stratosphere is characterized by a cold low centered near the pole which becomes more pronounced with increasing altitude. The cold low is surrounded by a band of strong west winds which are quite distinct from the strong tropospheric westerlies of lower latitudes. They are often called the "polar night westerlies" because the strongest winds occur at relatively high latitudes near the boundary of the polar night.

The polar atmospheric circulation in both hemispheres is also zonal during summer, but the winds are easterly, not westerly as in winter. The reversal of the circulation usually takes place over a short period of time, usually in a matter of a few weeks. The kinetic energy of the circulations is not negligible, for, although the densities are small in the trans-tropospheric region, the speeds of the air particles are large. Craig¹ has reviewed the data for winter months and cites as

an example a wind speed of 225 knots recorded at an altitude of 26 km. Although wind speed data at higher altitudes are not generally available, the temperature structure of the atmosphere indicates that wind speeds should increase with altitude to some unknown maximum. The higher altitude speeds are so large, in fact, that the integrated kinetic energy of the upper circulation is comparable to that of the lower. During some years, and especially over Canada and the United States, the reversals in wind direction and changes in density are spectacular.

At these times, the reversal of direction is said to be marked by the "breakdown" of the polar vortex. The density and wind variations are not like those accompanying local changes in air mass in the troposphere, since they involve areas of continental dimensions. Furthermore, there are no changes comparable in magnitude outside of the polar regions.

At present, it appears likely that the seasonal changes in polar regions are accompanied by: (a) rapid changes in the vertical distribution of ozone; (b) corresponding changes in total ozone in the same region^{2,3}; and (c) a difference in those respects between the two hemispheres. Teweles and Finger⁴ first showed that the changes in circulation accompanying the breakdown begin at high levels and proceed downward. There are no correlative observations that show that changes in ozone distribution above 30 km behave in the same fashion. In fact, no observations exist that could be used to relate variations with time of the distribution above 30 km, at and near the poles, with major disturbances of the circulation in those regions.

It has been suggested that ozone be used as a tracer of air motions during the breakdown. However, the distribution could so be used only if the ozone mixing ratio is a conservative property of the moving air

particles. While this may be so in the lower stratosphere, the distribution above the ozone maximum is probably not conservative because there are sources of ozone at high altitudes even in the polar night. During descending motion in the polar vortex (such as occurs during the breakdown) atomic oxygen is brought from low to high pressures with a consequent formation of new ozone. Furthermore, it may well be that proton bombardment of molecular oxygen in the auroral zone, which can occur as low as 60 km, produces atomic oxygen and, as a by-product, ozone.⁵ Hence, the problem of correlating circulation changes with changes in polar ozone is complicated and can only be attempted by making accurate observations of the vertical distribution of ozone above the maximum. In brief, the distributions would have to be accounted for in terms of (a) convection in the general sense, and (b) synthesis of ozone by collision processes of the two classes mentioned. These terms can be separated. The convection term can be studied if the large scale circulation and the distribution are known. The downward source term can be evaluated if the vertical motion is known. The proton source term (if any) can be separated out if observations are made at both poles.

It should be emphasized that the timing, intensity, and character of the polar vortex breakdown vary remarkably from year to year, as well as differing in the two hemispheres. To obtain correlations between ozone distributions and the vortex collapse, ozone measurements should preferably be made on a continuous basis. That is, drastic changes in ozone concentrations can be detected only if the time behavior of the distribution is known over a relatively long period of time.

Closely associated with the polar vortex breakdown is the "sudden" or "explosive stratospheric warming" first noted by Scherhag⁶. Immediately following the vortex collapse, there is observed a large increase in temperature in the mesospheric region. The warming propagates rapidly

from the mesosphere vertically downward into the stratosphere and has been detected over large areas in the arctic region and in fact throughout the entire high-latitude Northern Hemisphere. While the "sudden stratospheric warming" in the Northern Hemisphere occurs at various times between January and March, it has not been observed in the Southern Hemisphere before spring. The difference in timing of the vortex breakdown and associated sudden warming in the two hemispheres suggests that the topography of the two poles somehow plays a role in the development of the instability which causes the breakdown. However, the nature of this role and, in fact, the exact nature of the instability are not yet understood.

Godson³ has analyzed extensive data concerning the total atmospheric ozone content over arctic areas and concludes that ozone plays a major role in the buildup and collapse of the vortex. However, the relationships among atmospheric circulations, ozone, and temperature gradients are too complex, and observational data too sparse, to allow any definite explanation of the precise role played by ozone. In this connection, Godson states, "It will, of course, be evident that there is no satisfactory alternative to adequate data on the vertical distribution of ozone, available from a suitable network of stations. . . . If we had a good ozonesonde network, . . . it would then be possible to explain all variations on a day-to-day basis, and thus to arrive at explanations for the salient features on a longer period, including seasonal effects."

In the following section, it will be shown that the Nimbus satellites, by virtue of their orbits, provide a unique opportunity for obtaining continuous, synoptic data on the vertical ozone distribution in the vicinity of both poles.

3.2 NIMBUS SATELLITES AS VEHICLES FOR POLAR ATMOSPHERIC OZONE MEASUREMENTS

It is well known that the near-polar, sun-synchronous orbits of the Nimbus satellites are highly advantageous for remote radiation measurements, of meteorological significance, that are performed by earth-pointing sensors. These orbital characteristics ensure that extended observations over the sunlit and dark sides of the earth will be made during each orbit, and that they will also provide near local noon and midnight coverage at different longitudes on successive orbits. Most of the experiments planned for the Nimbus B and D flights are designed to exploit this type of earth coverage. However, the Nimbus orbits also prove to be ideal for another important class of experiments, namely those based on the phenomenon of solar occultation by the earth's atmosphere near the poles. It has long been recognized that the observation of solar radiation that passes tangentially through the earth's atmosphere provides a straightforward and accurate means of deducing the vertical distribution profile of atmospheric constituents. In this section, it will be shown that the occultation technique can be used to measure high-resolution vertical profiles of ozone density over the polar regions if appropriate optical instruments are mounted on the Nimbus satellites.

3.2.1 CHARACTERISTICS OF NIMBUS SATELLITE ORBIT

To make the Nimbus satellites sun-synchronous, the launch parameters are such as to cause the orbit to precess positively about the earth's polar axis at a rate of 360 degrees per year. The satellite is launched from Vandenberg AFB at midnight in a northwesterly direction with the result that a straight line from the center of the earth to the center of the sun always lies in the plane of the satellite orbit. The orbital angular momentum vector makes an angle of 100° with the earth's spin

axis, and the orbital plane is inclined to the equatorial plane by 80° . The orbit is circular, with a nominal altitude of 1100 km and a period of 1.79 hours.

The orbital characteristics noted above ensure that during each orbit the satellite will be in position to make a solar occultation measurement in the vicinity of each pole. The coverage provided by the satellite can be examined in terms of the sunset point of successive occultations, i.e., the geographical locations above which the vertical ozone profiles are determined. Since the period of the orbit is 1.79 hours, occultations occur in the vicinity of either pole at a rate of 13.4 a day. The earth's angular rotation rate is 360 degrees of longitude per day so that successive occultations occur at intervals of longitude equal to 26.8 degrees. The latitudes of the occultation points will depend both on the time of year of the launch and on the time elapsed after the launch. In general, the occultation latitudes will slowly oscillate between the extreme latitudes of 65° and 80° , with a period of six months. Figure 3-1 shows the Northern Hemisphere occultation points that would result during the first 48 hours following a late November launch. The pattern would be qualitatively identical for a launch at any other time of the year and also for the Southern Hemisphere. It is thus seen that if the orbital characteristics of the Nimbus satellites could be exploited for measuring atmospheric ozone by the solar occultation method, it would provide the basis for a new synoptic ozone climatology in high latitudes.

3.3 INSTRUMENTAL REQUIREMENTS OF OZONE MEASUREMENTS BY THE OCCULTATION METHOD

The optical and physical principles of the occultation method of ozone measurement have been discussed in detail in previous reports. The performance requirements that the measurement technique imposes on a satellite instrument will be reviewed here briefly.

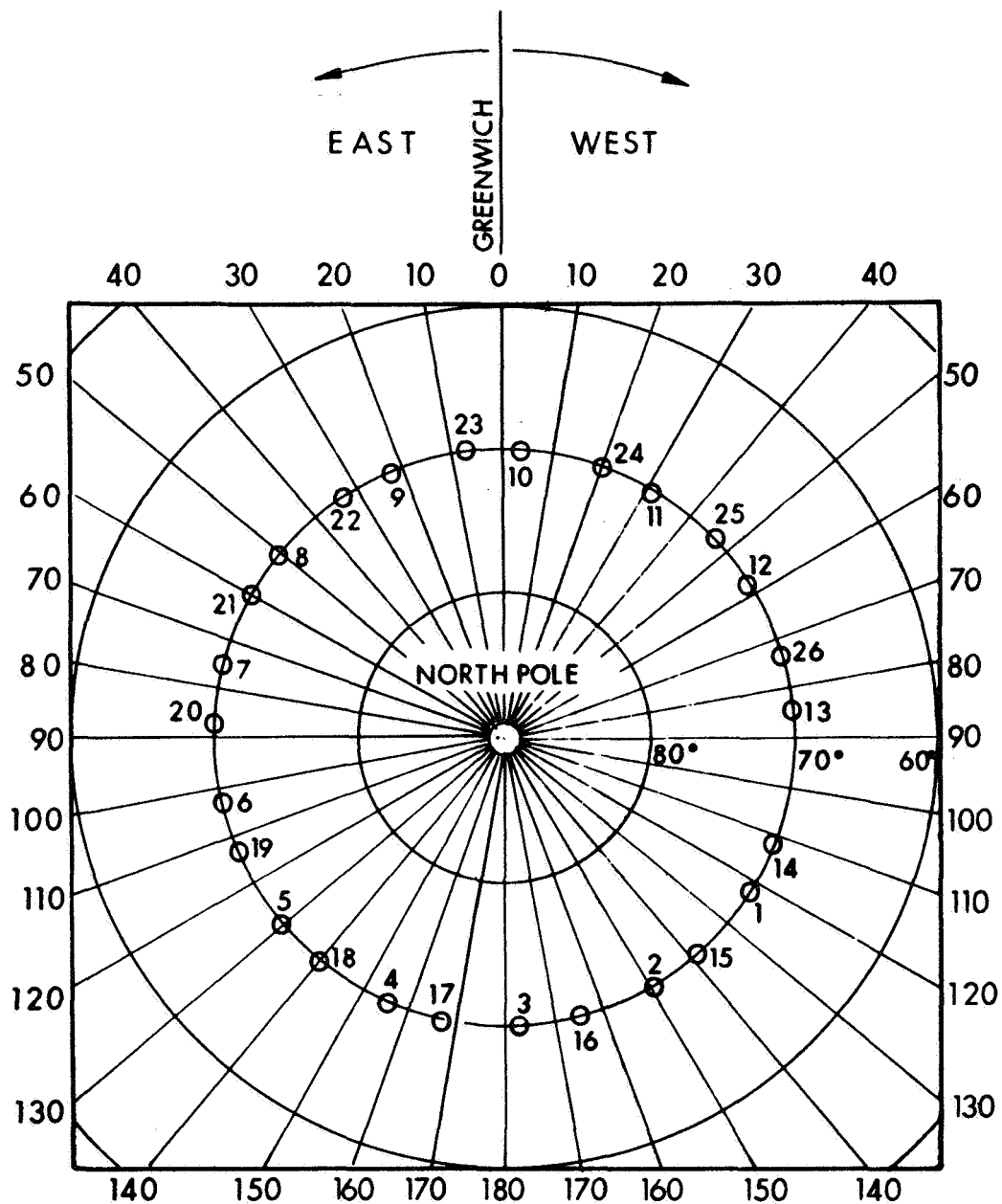


Figure 3-1. Northern Occultation Points During First 48 Hours of Nimbus Orbit, Assuming Late November, Midnight Launch from Vandenberg AFB. Similar Coverage (26 Occultations) Will Result in South Polar Regions During This Time.

3.3.1 SELECTION OF WAVELENGTHS TO BE MONITORED

Previous discussions have emphasized the fact that if the vertical ozone distribution is to be measured over an extended altitude range, the intensities of several wavelengths of solar radiation need to be monitored during one given occultation period. The reason for this is illustrated graphically in Fig. 3-2, which shows the molecular thicknesses of different tangential paths through the earth's atmosphere. The total number of air and ozone molecules were computed as a function of the altitude of closest approach of the solar rays to the sunset point on earth by using "standard" vertical distributions of air and ozone. The altitude range of interest in the polar circulation analysis discussed in Section 2 extends from 20 km to 70 km. It is seen that, in this range, both the air and ozone thicknesses vary by about three orders of magnitude.

Figure 3-2 can be transformed into an optical thickness curve for any given wavelength by weighting the air and ozone thicknesses, respectively, by the Rayleigh scattering cross section and absorption cross section per molecule, which are appropriate to that wavelength. This has been done for a number of wavelengths, as is shown in Fig. 3-3. A general criterion from absorption spectroscopy is that transmission measurements can be used for accurate quantitative determinations only within the transmission range of $0.05 < T < 0.95$. In terms of the optical thickness, τ , this means that useful measurements can be made only over altitude ranges corresponding to $3.0 > \tau > 0.05$. The curves in Fig. 3-3 thus demonstrate that any given wavelength can be used for ozone measurements only over a limited altitude range. If coverage is desired for the entire altitude range between 20 and 70 km, several wavelengths, such as those appearing in Fig. 3-3, would have to be utilized.

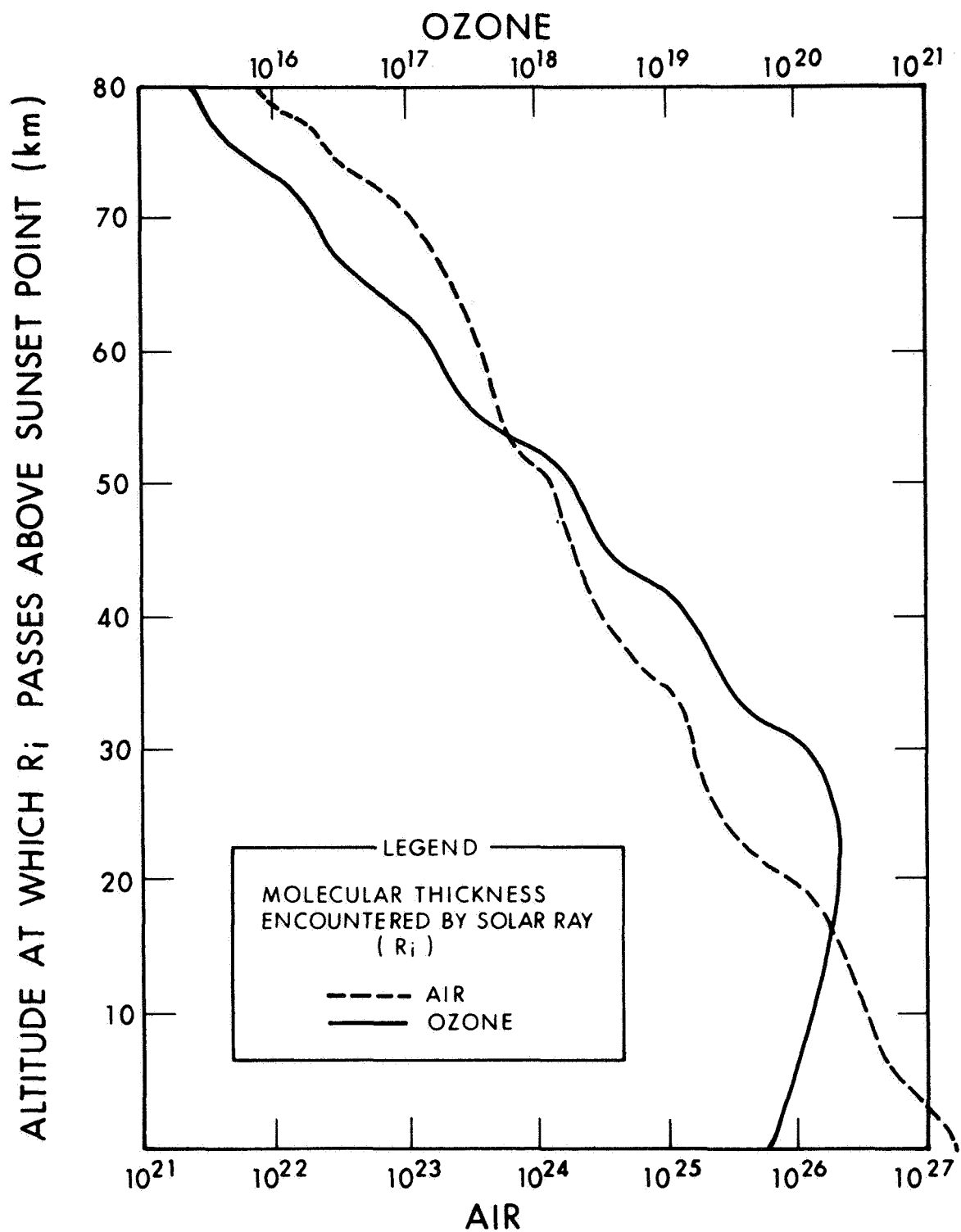


Figure 3-2. Total Number of Molecules Encountered by Tangential Rays as a Function of Altitude

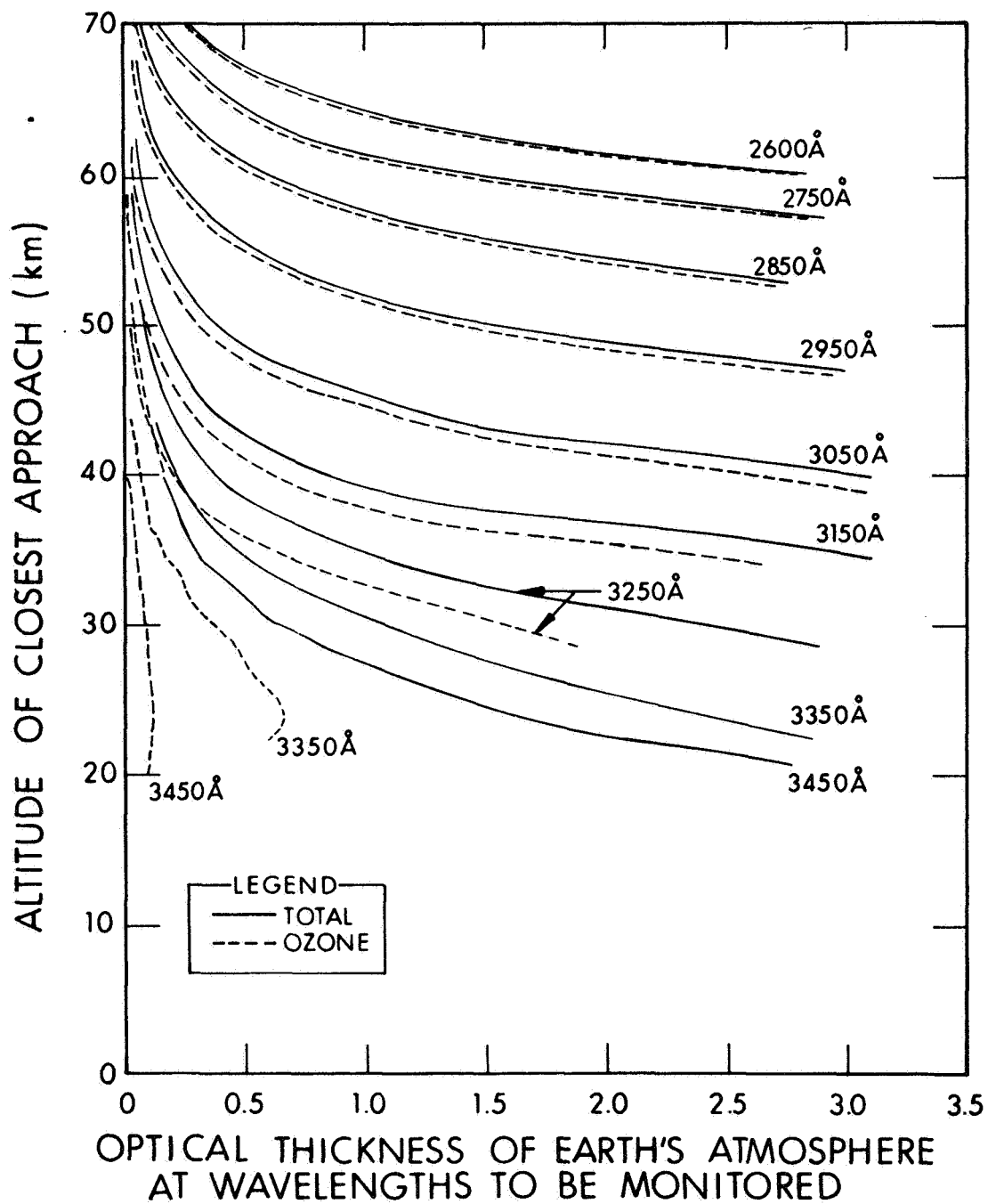


Figure 3-3. Optical Thickness of Earth's Atmosphere at Wavelengths to be Monitored

Further inspection of Fig. 3-3 shows that for any given altitude, useful transmission measurements can be made at only two or three of the wavelengths from among the set chosen for this illustration. The wavelengths were, in fact, chosen so that three wavelengths could be monitored at any given altitude, since this would provide a certain amount of desirable redundancy in the data. However, there is no need for continuous monitoring of all the wavelengths as the satellite scans the altitude range between 20 and 70 km, since this would result in the acquisition of large amounts of useless data. The instrument performing the measurements should therefore be capable of selecting at any instant that particular set of three wavelengths which should be monitored.

Finally, it should be recalled that the occultation method is self-calibrating. That is, transmission measurements are obtained by comparing the solar radiation intensity transmitted by the atmosphere to the direct solar intensity. For a number of reasons, it is desirable to measure the direct solar intensity when the satellite is in the same approximate orbital position as when it is making the occultation measurements.* The points S and S' in Fig. 3-4 indicate the relative positions of the satellite when it is making occultation measurements and when it is viewing the sun directly. For present purposes, the atmosphere can be considered to terminate at about 80 km, since above this altitude solar rays in the spectral region of interest pass through the atmosphere virtually unattenuated.

* These include the fact that the satellite instrument "on" control and pointing control need to be activated only once per occultation and the fact that polarization of the sunlight by the instrument optics will not change drastically if the angle of incidence of the solar radiation on the collection optics is approximately constant during the entire measurement sequence.

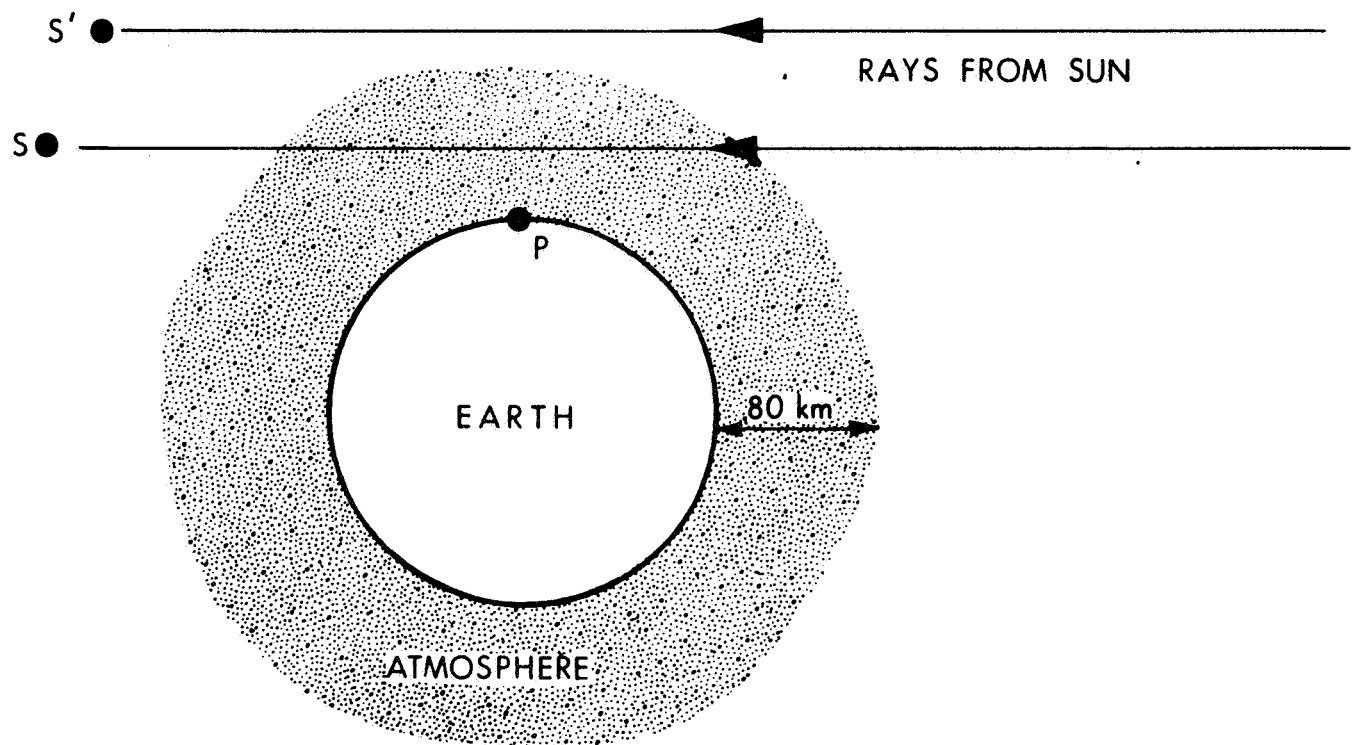


Figure 3-4. Geometry for Occultation Method of Measuring Ozone

3.3.2 INSTRUMENT POINTING REQUIREMENTS

As has been discussed in previous reports, one of the basic difficulties with the occultation method of measuring ozone is the fact that the sun as seen from a satellite is not a point source of radiation. The solar surface actually represents a finite disk of illumination whose rays traverse the atmosphere through widely varying paths. This circumstance has introduced large uncertainties in the results of previous attempts to measure atmospheric ozone from satellites by the occultation technique.⁷⁻¹⁰ Referring to Fig. 3-5, it is seen that if the instrument is allowed to view the entire solar disk, the ozone distributions that are derived are "blurred" over a large altitude range. However, high-resolution vertical profiles can be obtained if image-slicing optics are incorporated into the instrument such that the sun can virtually be rendered into a thin horizontal line source of radiation.

As viewed from the altitude of the Nimbus satellites, the solar disk projection would correspond to an altitude interval of some 35 km above the sunset point, P. If the image-slicing optics restrict the instrument's field of view so that it accepts radiation from a slice of the disk whose thickness is approximately 1/10 of the solar diameter, the altitude increment of a given measurement is reduced to some 3 to 4 km. This image-slicing capability will be defined here as one of the criteria which the Nimbus instrument must satisfy.

3.3.3 TIME DURATION OF OCCULTATION MEASUREMENTS AND TIME-CODING OF DATA

The position of the orbit in which the satellite views the sun through the earth's atmosphere, as in Fig. 3-4, is traversed in a matter of 25 to 30 seconds. A straight line from the Nimbus satellite to the center of the sun would scan the 20 km to 70 km altitude above P at the rate of 3.8 km sec^{-1} . Therefore, to preserve the vertical resolution capability of the pointing and image-slicing components of the instrument,

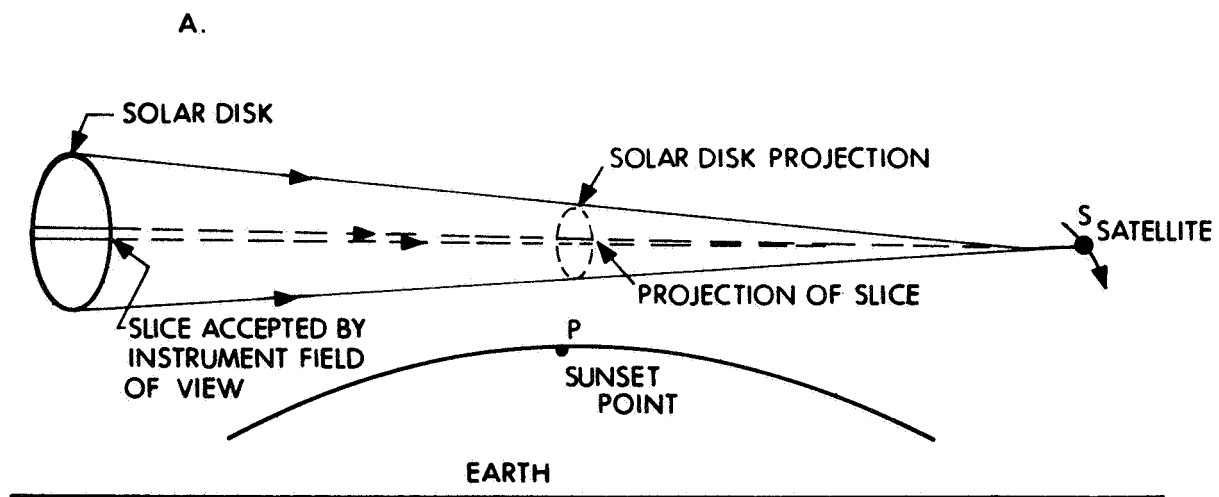


Figure 3-5. Geometry of Satellite Illumination

solar intensity recordings should be made within a fraction of a second. Assuming that photoelectric detectors are utilized for the intensity measurements, this imposes a limit on the signal integration time for each wavelength recording.

It is obvious that the exact position of the satellite at the time of each intensity recording must be known so that accurate ozone profiles can be deduced from the data. Therefore, any data that is telemetered should be identified with the time of the recording, as provided by a clock carried by the satellite. The satellite position corresponding to each intensity reading can thus be determined from orbital data.

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3.4 INSTRUMENT DESIGN

3.4.1 FUNCTIONAL DESCRIPTION

The geometrical relationships between the sun, the earth, and the spacecraft are shown in Fig. 3-6. To measure atmospheric transmission in both polar regions from an earth-oriented spacecraft requires the instrument to accept incident light from two directions relative to the spacecraft. The angle β between the central solar ray and the local vertical is given by

$$\beta = \sin^{-1} \frac{R_E + H}{R_O},$$

where

$$R_E = \text{earth radius} = 6400 \text{ km},$$

$$R_O = \text{orbital altitude} = 1100 \text{ km},$$

$$H = \text{altitude of the transmitted ray in the terminator plane},$$

from which

$$\beta = 58.7^\circ \text{ at } H = 0$$

and

$$\beta = 60.7^\circ \text{ at } H = 140 \text{ km}.$$

The block diagram of the instrument is shown in Fig. 3-7. Two entrance paths are provided to accommodate the sun-earth-spacecraft geometry at both polar regions of the earth. The transmitted sunlight enters through path 1 at the north polar occultation and through path 2 at the south

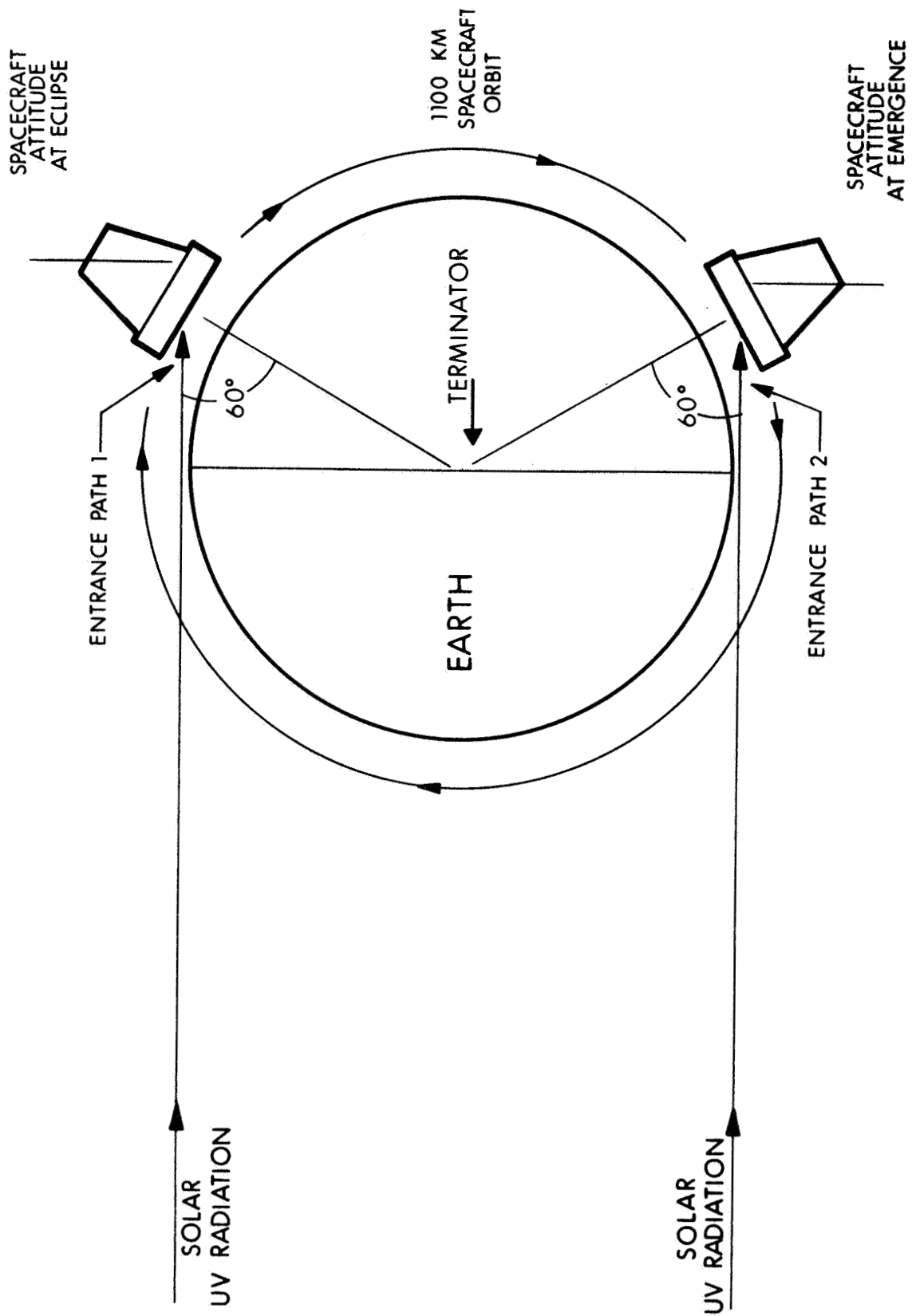


Figure 3-6. Orbital Geometry of the Occultation

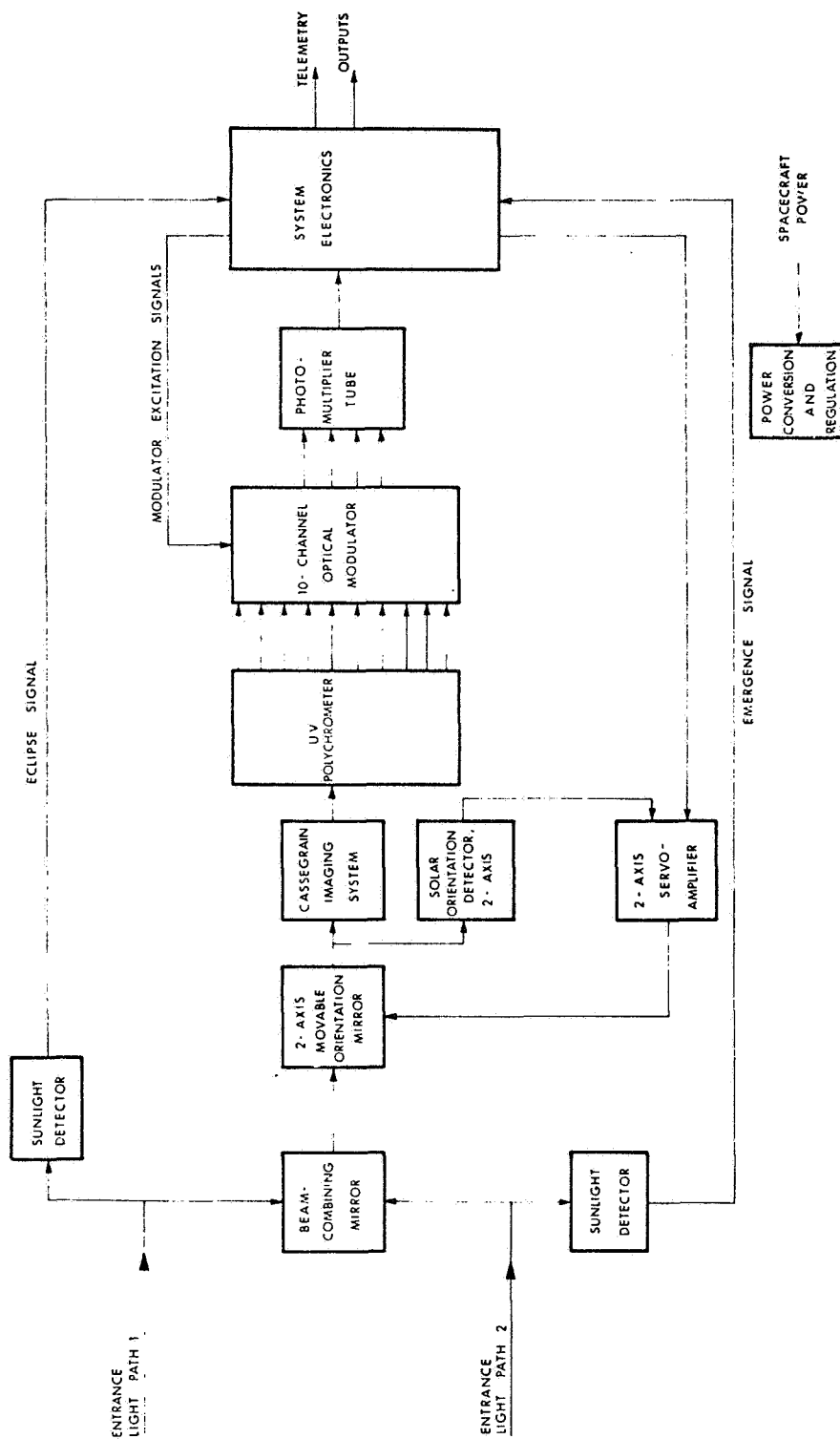


Figure 3-7. Ultraviolet Spectrometer Block Diagram

polar occultation. It is assumed here that the spacecraft is in a polar orbit such that it enters the earth's shadow in the north polar regions.

The two entrance light paths are combined by a fixed beam-combining mirror, such that one beam is above and one is below the meridional plane of the instrument. A servo-controlled orientation mirror compensates for spacecraft motions and maintains the image of the solar disc in a fixed relationship to the polychromator entrance slit. The position of the orientation mirror is controlled in two axes by an optical orientation detector and a servoamplifier, which control the motor-driven mirror positioning mechanism.

A Cassegrain telescope with a hyperboloidal secondary reflector images the sun in the plane of the polychromator entrance slit. A fixed-grating UV polychromator is used to separate the ten wavelength bands of interest. These bands are on the order of $10\text{\AA}$ wide, spaced at $100\text{\AA}$ intervals from $2600\text{\AA}$ to $3500\text{\AA}$. A tenth band is centered at $3800\text{\AA}$. A series of 10 optical modulators chop the 10 spectral band outputs of the polychromator. Chopping of each band is achieved by means of an opaque vane attached to a tuning fork, the oscillation of which periodically blocks the light transmission through the system. The frequencies of oscillation of the 10 tuning forks are separated from each other to enable synchronous detection of the individual wavelength bands. A field lens combines the chopped light output of the modulators and distributes the energy across the cathode of the photodetector. A preliminary analysis indicates that the light level will be great enough to enable the use of either a vacuum photodiode or a photomultiplier detector.

The system electronics amplifies and demodulates the output of the photomultiplier tube and produces a digital data output for telemetry. An automatic data selection system selects the most pertinent wavelength bands for measurement. The selection criteria are as follows.

As the spacecraft enters the earth's shadow, the upper atmospheric layers attenuate the shortest wavelengths first, and the longer wavelengths are

relatively unattenuated. As the spacecraft descends further into the shadow, progressively longer wavelengths are attenuated. The process is reversed upon emergence from the shadow. On entering the shadow, the system measures the three shortest wavelength bands, λ_1 , λ_2 , and λ_3 , and transmits their intensities to telemetry. When the intensity of the shortest band, λ_1 , drops below some predetermined minimum, the system rejects λ_1 , substitutes λ_4 in its place, and monitors λ_2 to determine the next switching. Thus the system continues measuring three consecutive bands, rejecting the shortest wavelengths as they diminish and measuring progressively longer bands until the sequence ends with the selection of λ_7 , λ_8 , and λ_9 . The longest wavelength, $\lambda_{10} = 3800\text{\AA}$, is measured continuously throughout the sequence.

On emerging from the eclipse, a slightly different criterion is used to avoid the need of measuring a wavelength band which is not telemetered. The system begins the emergence sequence, measuring the three longest bands, λ_7 , λ_8 , λ_9 , and monitoring the center band of the three. As λ_8 increases to a predetermined maximum, the system rejects λ_9 , substitutes λ_6 , and monitors λ_7 . This sequence continues until it ends with the selection of λ_1 , λ_2 , and λ_3 .

When the spacecraft emerges to the point where the incident solar rays pass more than 100 kilometers above the earth's surface, the system measures all of the nine wavelength bands sequentially for use in calculating atmospheric transmission. As the spacecraft approaches the eclipse, the nine bands are measured and stored in the electronics for use in the automatic data selection.

For the nominal 1100-kilometer Nimbus orbit, the system measures direct solar radiation at altitudes of closest approach of 140 to 100 kilometers and measures atmospheric transmission between 100 and about 10 kilometers. The total elapsed time, neglecting atmospheric refraction, to transit from 140 to 0 kilometers is 36 seconds, assuming a circular orbit. For the remainder of the period of the orbit the system is inactive. The

system senses an impending eclipse or emergence by means of photoresistive detectors which detect sunlight entering through either entrance path. The signals from the respective detectors are used to start the eclipse or emergence sequence of the instrument.

3.4.2 SIGNAL AND SIGNAL-TO-NOISE RATIO CONSIDERATIONS

This section will be concerned with developing the signal at the photocathode of the photoemissive detector and the effects and sources of noise present in the system. Based on assumptions made from these considerations, calculations will be made to determine the required size of the collection optics and to estimate system performance.

3.4.3 SIGNAL

The signal power at the detector is determined by the source signal, collecting optics size, slit size, optical efficiency of the system, atmospheric transmission, and the system electrical bandwidth.

The incident power at the detector, P_λ , is given by

$$P_\lambda = \tau N_\lambda \Omega A_s \Delta_\lambda, \quad (1)$$

where

$$\tau = \tau_a \tau_o,$$

$$\tau_a = \text{atmospheric transmission} = 0.1 \text{ (worst case),}$$

$$\tau_o = \text{optical efficiency of system} = 0.25,$$

$$\Delta_\lambda = \text{spectral bandwidth,}$$

$$\Omega = \frac{\pi D^2}{4 f'^2},$$

$$D = \text{collecting optics diameter,}$$

$$N_\lambda = \text{spectral radiance} = \frac{4 H_\lambda}{\pi \theta^2},$$

$$H_\lambda = \text{spectral irradiance,}$$

$$\theta = \text{solar subtense} = 9.4 \times 10^{-3} \text{ rad,}$$

$$A_s = \text{area of the slit,}$$

and f' = focal length of the collecting optics,

which yields

$$P_{\lambda} = \frac{\tau H_{\lambda} D^2 A_s \Delta \lambda}{\theta^2 (f')^2} \text{ watts.} \quad (2)$$

The slit area is

$$A_s = \frac{W^2}{k}, \quad (3)$$

where

W = slit width

and k = slit aspect ratio.

The slit width is related to the polychromator parameters by

$$W = \frac{\Delta \lambda f}{(a^2 - \lambda^2)^{1/2}} \approx \frac{\Delta \lambda f}{a}, \quad (4)$$

since $a^2 \gg \lambda^2$,

where

f = monochromator focal length,

a = grating spacing,

and λ = wavelength.

Therefore substituting for A_s in Eq. 2,

$$P_{\lambda} = \frac{\tau H_{\lambda} D^2 \Delta \lambda^3 f^2}{\theta^2 (f')^2 k (a^2 - \lambda^2)} \text{ watts,} \quad (5)$$

or

$$P_{\lambda} = \frac{\tau H_{\lambda} D^2 \Delta \lambda W^2}{\theta^2 (f')^2 k} \text{ watts.} \quad (6)$$

Photoemissive detectors convert photons into photoelectrons with quantum efficiency η . The photocathode signal current is given by

$$\begin{aligned} I_s &= \frac{\eta e P_{\lambda}}{h \gamma} \\ &= \frac{\eta e H_{\lambda} D^2 \Delta \lambda W^2}{\theta^2 (f')^2 k h \gamma}, \end{aligned} \quad (7)$$

where

e = electron charge,

h = Plank's constant,

and γ = optical frequency.

The parameters f' , $\Delta\lambda$, and W are interrelated and will be discussed at this time.

The physical size of the chopping mechanism at the spectral focal plane will determine the focal length of the monochromator. Calculations indicate that a 30-cm focal length and a 10,000Å grating spacing yields a spectral plane dispersion of 3 millimeters per 100Å. This dimension is sufficient for the mechanism under consideration.

The spatial resolution of the instrument is defined as the range of minimum altitudes subtended by the extremal rays entering the polychromator slit. It determines the minimum altitude element over which the instrument is capable of measuring atmospheric absorption.

The instantaneous spatial resolution Δh is given by

$$\Delta h = \alpha S, \quad (8)$$

where

S = the distance from the instrument to the terminator plane

$\approx 3.9 \times 10^3$ km for an 1100-km orbit,

and α = the field of view subtended by the polychromator slit width, W .

Then

$$\alpha = \frac{W}{f'}, \quad (9)$$

where f' is the focal length of the collecting optics. The value of α is selected to yield a suitably small value of the spatial resolution, Δh . The value $\alpha = 5 \times 10^{-4}$ radians corresponds to $\Delta h = 2$ kilometers. Combining equations 4 and 8 yields

$$f' = \frac{\Delta\lambda f}{\alpha a}. \quad (10)$$

Therefore, a spectral bandwidth of $2.5\text{\AA}$ yields a slit width of 0.075 mm and a collector focal length of 15 cm at $\alpha = 5 \times 10^{-4}$ radians.

Photocathode signal current can now be computed from Eq. 7 and is illustrated in Fig. 3-8 as a function of collector diameter. The parameters are:

$$\begin{aligned}\eta &= 0.2 \text{ (ITT F4018 (S5) photodiode)} \\ e &= 1.6 \times 10^{19} \text{ coulombs} \\ \tau_a &= 0.1 \text{ (worst case)} \\ \tau_o &= 0.25 \\ \Delta\lambda &= 2.5 \\ W &= 0.075 \text{ mm} \\ \theta &= 9.4 \times 10^{-3} \text{ radians} \\ f' &= 15 \text{ cm} \\ k &= 1/6 \\ \lambda &= 2600\text{\AA} \text{ and } 3330\text{\AA} \\ H_{2600} &= 14 \times 10^{-7} \text{ W/cm}^2 - \text{\AA} \\ H_{3330} &= 112 \times 10^{-7} \text{ W/cm}^2 - \text{\AA} \\ a &= 10,000\text{\AA} \\ f &= 30 \text{ cm} \\ h &= 6.63 \times 10^{-34} \text{ joule/sec} \\ \alpha &= 5 \times 10^{-4} \text{ radians}\end{aligned}$$

Figure 3-8 illustrates the extreme condition, that is, atmospheric transmission = 0.1, which is the minimum value of interest. The photocathode signal extremes for a 0.5-cm collecting diameter are therefore from 10^{-11} to 10^{-8} amp. The anode current of a photomultiplier tube with a gain at 10^4 will therefore vary from 10^{-7} to 10^{-4} amp.

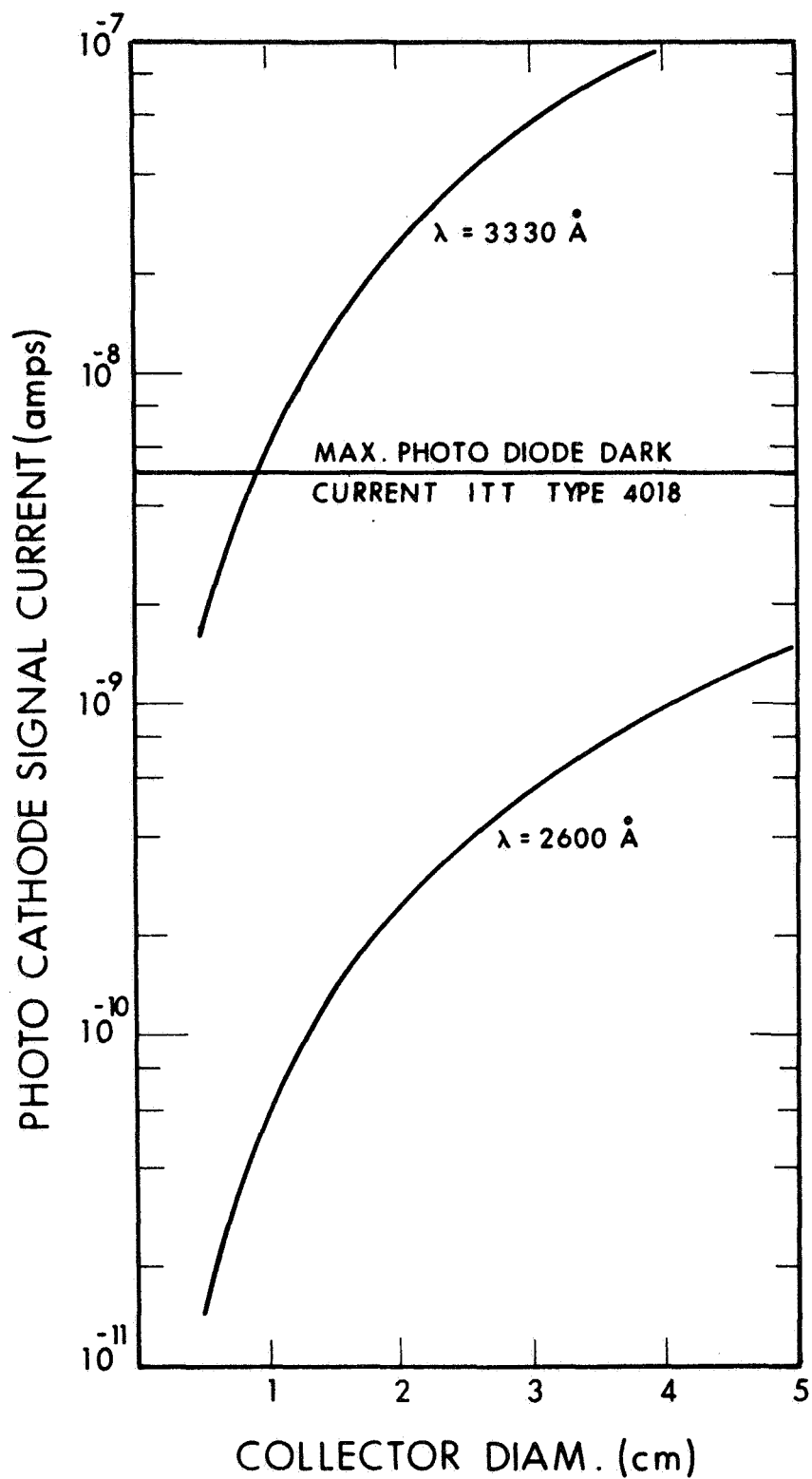


Figure 3-8. Photocathode Signal versus Collection Optics Diameter

3.4.4 SIGNAL-TO-NOISE RATIO

There are three sources of noise in an optical receiver system: electronic, background, and detector. Electronic noise produced by components is generally neglected with the use of photomultipliers but is considered here in the case of the photodiode. Background noise can be neglected, since the field of view and pointing system constrain the system to look at the center of the sun. Detector noise is caused by the random nature of photoemission, ohmic leakage, and certain regenerative effects which manifest themselves as dark current.

The system signal-to-noise ratio is directly proportional to the signal current and inversely proportional to the square root of the signal and noise current and is given by

$$\text{SNR} = \frac{I_s}{(2eI_t + 4FkT/GR_L)^{1/2} (\Delta f)^{1/2}}, \quad (11)$$

where $I_t = I_s + I_D + I_{BG}$,
 I_D = detector dark current = 5×10^{-9} (ITT 4018 (S5)),
 I_{BG} = current resulting from background sources,
 Δf = electronic bandwidth = 1/3 Hz,
 I_s is given by Eq. 7,
 $F = 10 \text{ NF}/10$ = antilogarithm of the amplifier noise figure,
 k = Boltzmann's constant = 1.38×10^{-23}
 T = temperature of the amplifier,
 G = electron multiplication of the detector
($G = 1$ for the vacuum photodiode), and
 R_L = transresistance of the amplifier.

Figure 3-9 illustrates the signal-to-noise ratio as a function of collector diameter for the minimum signal condition corresponding to $\lambda = 2600\text{\AA}$ and $\tau_a = 0.1$, with a photodiode detector. The figure indicates that a satisfactory signal-to-noise ratio is achievable without the need for the amplification of a photomultiplier.

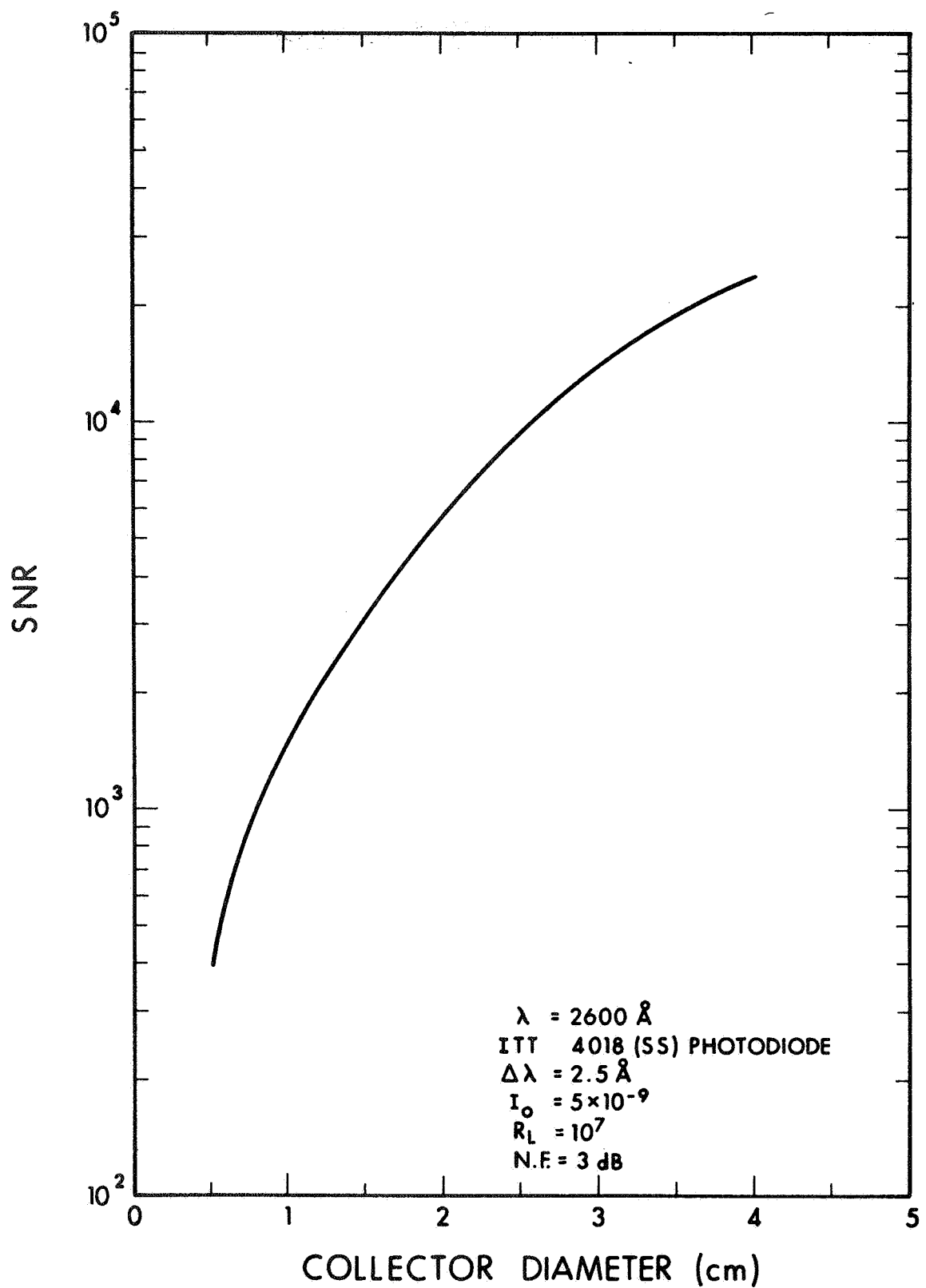


Figure 3-9. Signal-to-Noise Ratio versus Collection Optics Diameter

3.5 OPTICAL DESIGN

3.5.1 ORIENTATION OPTICS

The optical layout of the instrument is shown in Fig. 3-10. Light entering the instrument through either of the two paths is reflected from one of the two fixed mirrors to the movable orientation mirrors. The two orientation mirrors are fixed in relationship to each other and move together as a unit to stabilize the image of the solar disk. With this method of beam-combining alternate halves of the collection and polychromator optics are utilized for light entering through the two entrance paths. The movable orientation mirrors are positioned by a motor-driven mechanism with a total angular travel of $\pm 3^\circ$ about two axes. This angular freedom compensates for a total instrument misalignment of 6° relative to the sun. As the instrument views the sun from the earth-oriented spacecraft, the sun appears to move as the spacecraft advances in its orbit. A sun-spacecraft-local vertical angular range of 58.7° to 60.7° corresponds to an altitude range of 0 to 140 kilometers for a 1100-kilometer orbit. This 2° tracking capability is sufficient to enable measuring both the occulted and unocculted radiation from the sun. In addition to the tracking capability, the orientation system is able to compensate for $\pm 1.5^\circ$ spacecraft orientation errors and instrument misalignments.

The prime movers are two permanent-magnet dc stepping motors. This type of motor is chosen for its positive displacement characteristic, which permits the design of a high-performance servo without a need for tachometer stabilization. Its small size and reliable construction permit its use in sealed mechanisms where long operating life is important. The mirror drive mechanism is enclosed and hermetically sealed to preserve lubrication integrity in space. A flexible seal to permit mirror motion is provided by a metal bellows between the housing and the mirror mount.

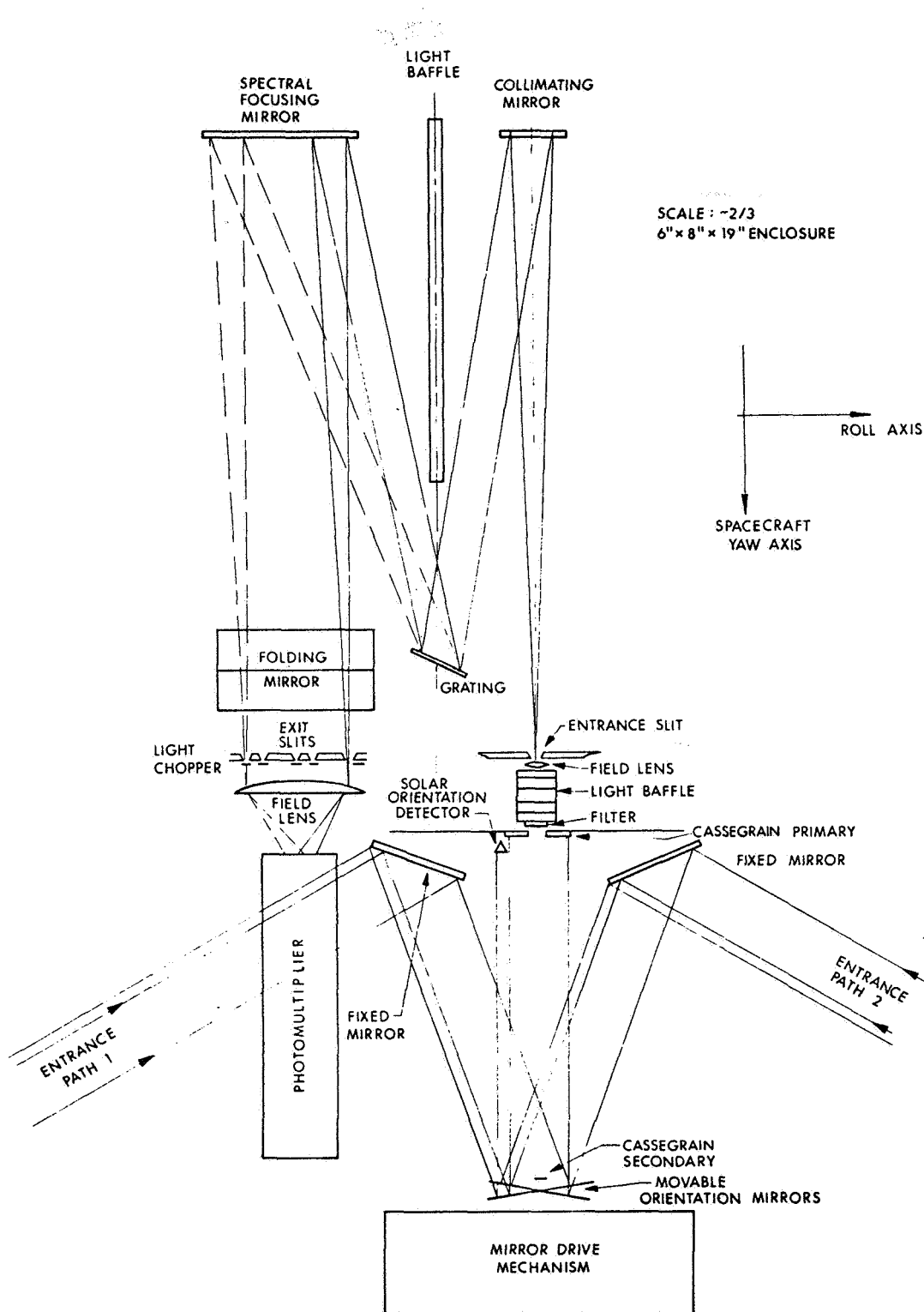


Figure 3-10. Ultraviolet Spectrometer Optical Layout

3.5.2 SOLAR ORIENTATION DETECTOR

The orientation mirror is positioned to maintain the central ray from the sun parallel to the axis of the Cassegrain telescope. A two-axis solar orientation detector mounted on the edge of the Cassegrain primary detects any deviation from the desired orientation and produces suitable error signals for controlling the servo. The operation of the sensing unit is illustrated in Fig. 3-11. It consists of a glass prism cut to the critical angle of reflectance and two silicon photovoltaic detectors connected in opposition. When the sun is in the plane bisecting the prism, the detectors are equally illuminated and no output is produced. However, when the sun deviates from this plane, the angle of incidence on one face of the prism increases, and the amount of light transmitted to the respective detector decreases due to the nearly total internal reflection. Similarly the illumination of the opposite detector increases and an output signal is produced. An identical device oriented in an orthogonal direction is used to sense about an orthogonal axis.

These devices demonstrate excellent reliability and accuracy due to their simplicity. In this application a null stability better than 30 seconds of arc is readily achievable.

3.5.3 COLLECTION OPTICS

The collection optics shown in Fig. 3-10 consist primarily of a paraboloidal primary which receives light from the plane orientation mirror. This paraboloid directs its radiation to the hyperboloidal secondary of the on-axis Cassegrain system which focuses an image of the sun on the entrance slit.

It is necessary that the maximum blur circle from defocusing effects and aberrations, primarily coma, be such that the image of the sun is not blurred beyond the limits of the basic solar resolution element. The aberration of coma would cause this component of the blur circle to be maximum at the top and bottom of the slit.

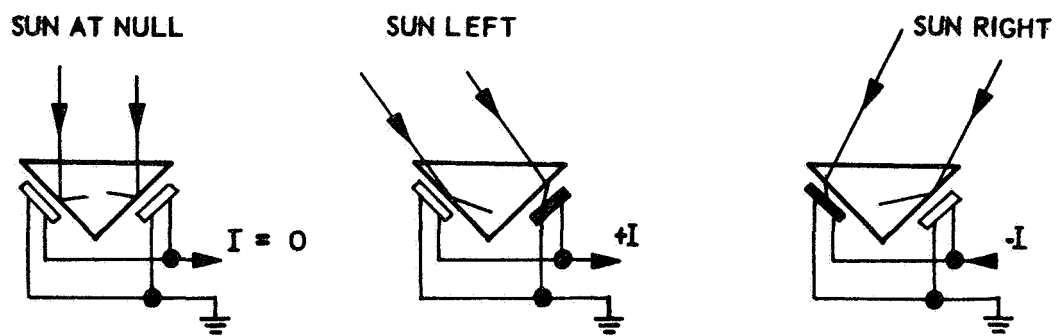


Figure 3-11. Solar Orientation Detector

A Cassegrain system is more suitable than a simple paraboloid because of the high magnification required at the entrance slit.

3.5.4 POLYCHROMATOR

The polychromator is the basic Czerny-Turner spectrograph design. It is shown in Fig. 3-10 as being coma-corrected for the center wavelength by virtue of the smaller effective aperture and larger field angle for the center wavelength in the dispersed radiation space. This coma correction may not be necessary because of the predominance of astigmatic blur increasing at greater distances from the meridional plane. This is a result of the need for straight slits, preventing the use of the optimum curved (near circular) slits for the Czerny-Turner. The straight slits are, of course, required because of the need to preserve the integrity of the basic solar resolution element.

The grating center is placed at approximately 0.43 times the radius of the polychromator mirrors from these mirrors to insure flatness of field on a spectrum whose focal plane intersects the meridional plane in a straight line. Due to the f:15 entrance angle, the polychromator mirrors can in all probability be spheres. Besides allowing the use of spheres and reducing other aperture-dependent aberration constraints, the f:15 entrance angle increases the depth of field at the slits and thereby reduces adverse thermal effects, tending for instance to change focal lengths of mirrors and overall structure length. The constraining equations for the polychromator geometry are developed in the subsequent paragraphs.

An ultraviolet transmitting interference filter is situated at the entrance to a light baffle between the Cassegrain secondary. The interference filter is used to eliminate that portion of the sun's radiation occurring at wavelengths greater than $4000\text{\AA}$, since these can contribute heavily to a scattered light signal. The long wavelength limit is such as to make questionable the advisability of a solar-blind photomultiplier so that scattered light can become an important addition to the signal of interest, even with UV photomultipliers whose spectral responses begin to fall off at about $7000\text{\AA}$. The

filter can also be designed to protect itself as well as the field lens at the entrance slit from optically degrading ultraviolet radiation, should this be considered necessary.

A field lens exists at the entrance slit for the purpose of focusing the secondary of the Cassegrain onto the grating. Besides conserving radiant energy, this lens also is helpful in reducing scattered light. Use of a field lens at the entrance slit becomes advisable when the element preceding it (the Cassegrain secondary) approaches the slit height in linear dimensions.

The grating is a 50,000-line-per-inch replica mounted in a fixed orientation. A folding mirror lies between the exit slits and the spectral focusing mirror because of the need to observe the sun along two lines symmetrically disposed about the axis of the spacecraft and separated by 120° . Such a constraint does not allow positioning of a detector in the normal polychromator position.

A field lens lies just beyond the exit slit array and vibrating-reed modulator assembly. A photomultiplier whose photocathode lay at the focal length of the field lens would have all spectral bundles superimposed on its photocathode.

3.5.4.1 First-Order Constraints for Czerny-Turner Geometry

A first-order analysis is used to generate the families of Czerny-Turner systems each with a given f/number and grating spacing for an optimization study. In each case, the asymmetry in focusing and collimating mirror angle which is necessary to remove coma from the central wavelength is calculated*. The geometry of each configuration includes this coma-correcting asymmetry. (See Fig. 3-12.)

$$D_2 - D_3 = 1.2 D_1 \quad \text{(to keep radiation in wavelengths (1) shorter than } \lambda_1 \text{ from focusing on grating; the 1.2 factor is to allow space for mechanical components such as an intermediate slit or deflecting mirror)}$$

$$\tan \gamma = \frac{D_1/2 + D_2}{0.422 R} \quad \text{(geometry; R is radius of curvature (2) of spherical mirror centered at O in the figure)}$$

$$\tan \gamma = \frac{\frac{D_1}{2} + 1.2 D_1 + D_3}{0.422 R} = \frac{1.7 D_1 + D_3}{0.422 R} \quad \text{[combine 1 and 2]} \quad (3)$$

$$C_2 = \sin \theta_1 + \sin \theta_{22} \quad \text{grating equation where} \quad (4)$$

$$C_1 = \sin \theta_1 + \sin \theta_{21} \quad \text{C = } \lambda/a, \lambda = \text{wavelength,} \quad (5)$$

$$C_0 = \sin \theta_1 + \sin \theta \quad \text{a = grating constant, } \theta_{22}, \theta_{21}, \theta_{20} \text{ are diffraction angles at } \lambda_2, \lambda_1, \lambda_0, \text{ respectively. } \theta \text{ is the angle of incidence.} \quad (6)$$

* A. B. Shafer, L. R. Megill, and LeAnn Droppleman, J. Opt. Soc. Am., 54, 879 (1964)

$$D_3 = k_3 \times 0.422 R \quad (k = \text{proportionality constant which (7) refers all distances to R})$$

$$D_1 = 0.422 \frac{R}{\#}; \quad (\# = 7, 9, 15, 23) \quad (8)$$

(where # denotes f/number)

$$\tan \gamma = \frac{1.7}{\#} + k_3 \quad [\text{combine Eqs. 3, 7, and 8}] \quad (9)$$

$$-\theta_1 + \theta_{20} = 2 \gamma \quad (\text{Geometry}) \quad (10)$$

$$\frac{R}{2} \tan \frac{|\theta_{21} - \theta_{22}|}{2} = D_3 \quad (11)$$

$$\text{or, } \tan \frac{|\theta_{21} - \theta_{22}|}{2} = 0.845 k_3$$

Equations 4, 5, 6, 9, 10, and 11 are six equations in six unknowns, $\gamma, \theta_{20}, \theta_{21}, \theta_{22}, \theta_1, k_3$ with #, C_0, C_1, C_2 the varying parameters. The C_0, C_1 , and C_2 , parameters should be varied in the following manner: At each value of #, C_0, C_1 , and C_2 should take on the three values in each of the following four groups.

0.102,	0.171,	0.240	(600 grooves/mm)
0.204,	0.342,	0.480	(1200 grooves/mm)
0.408,	0.684,	0.960	(2400 grooves/mm)

The grating spacing or constant (a) is the reciprocal of the number of grooves/mm.

Once $\theta_1, \theta_{20}, \theta_{21}$, and γ have been solved for, a solution for Γ (see Fig. II-9) may be obtained from the following equation, which eliminates coma at λ_0 .

$$\frac{\cos^3 \theta_1}{\cos^3 \theta_{20}} = \frac{\sin \gamma}{\cos^3 \gamma} \frac{\cos^3 \Gamma}{\sin \Gamma} \quad (12)$$

The five constraint equations are grouped as follows:

$$\tan \frac{\theta_{20} - \theta_1}{2} = \frac{1.7}{\#} + k_3 \quad (9)$$

$$\theta_2 = \sin \theta_1 + \sin \theta_{22} \quad (4)$$

$$C_1 = \sin \theta_1 + \sin \theta_{21} \quad (5)$$

$$C_o = \sin \theta_1 + \sin \theta_{20} \quad (6)$$

$$\tan \frac{\theta_{21} - \theta_{22}}{2} = 0.845 k_3 \quad (11)$$

3.5.5 OPTICAL MODULATOR

The design of the optical modulator is shown in Fig. 3-13. The modulator utilizes a mask in the spectral plane having 10 apertures through which light in the 10 spectral wavelength bands is transmitted. Ten individually controlled vanes interrupt the light transmitted through the respective apertures. To preserve the simplicity of the diagram Fig. 3-13 shows only a section of the mask and one of the ten tuning forks. As shown in the diagram, the light-chopping vane is mounted on the end of one tine of the tuning fork. The oscillatory motion of the fork displaces the vane in the plane of the mask, thereby periodically interrupting the light path. The opposite tine of the fork serves no function other than providing dynamic mass balance of the assembly.

The tuning fork is shown in the neutral or unenergized position. When excited, the vane has equal displacements to the left and to the right of this neutral position. The vane is located so that the aperture is blocked in the neutral position and unblocked for rightward displacements. This arrangement was chosen to minimize the light reaching the detector from unenergized choppers.

The complete 10-channel modulator consists of 10 tuning forks with attached vanes modulating the light in 10 respective wavelength bands. To make the assembly as compact as possible, the locations of the forks are staggered with respect to the spectral plane. In the diagram, a part of a fork located above the mask is shown. Two additional fork locations, not shown in the diagram, are on the opposite side of the mask.

In operation the system is required to analyze only four spectral wavelength bands at any one time. To improve the signal-to-noise ratio it

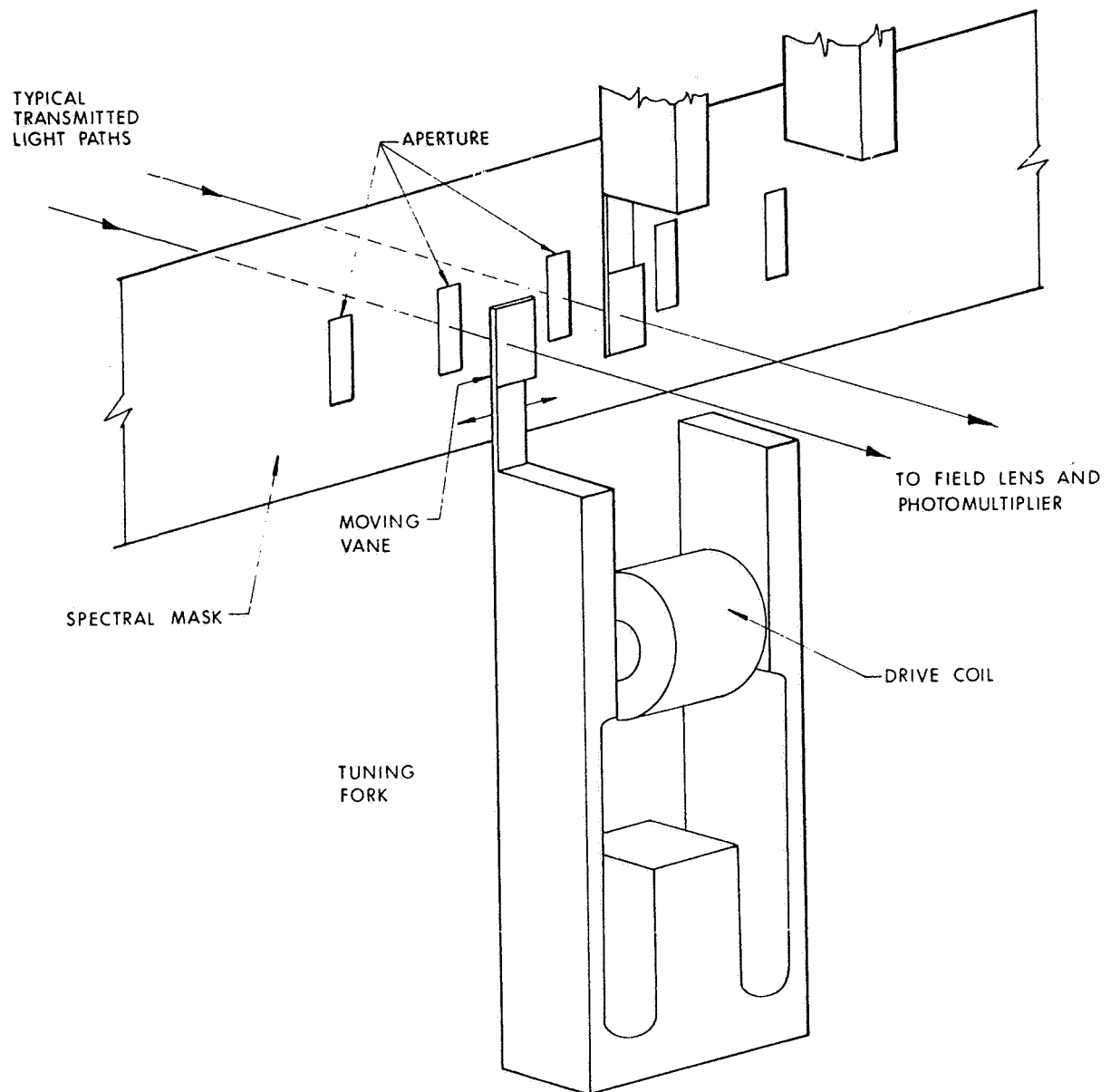


Figure 3-13. Optical Modulator

is desirable to minimize the light reaching the photodetector from sources other than the signals being analyzed. This is particularly important at the shortest wavelengths, where the incident energy is a minimum. This light reduction is accomplished by turning off the modulators corresponding to the unused wavelength bands. A further advantage of this technique is that a smaller number of different tuning fork frequencies is required, since only four forks are operating at any one time. The tuning fork drive circuitry is specially designed to permit rapid on-and-off switching of the modulators.

3.6 SYSTEM ELECTRONICS

The system electronics performs the synchronous detection of signals corresponding to the 10 wavelength bands and selects the proper signals for transmittal to telemetry. This selection is controlled by internal digital storage and logic circuitry on the basis of the measured intensity of the demodulated signal. The electronics also includes circuitry for driving the tuning forks in the optical modulator.

A block diagram of the system electronics is shown in Fig. 3-14. While a preliminary signal-to-noise analysis indicates the possibility of using a diode photodetector, the block diagram shows a photomultiplier. With either type of detector, the block diagram would be essentially the same except that an amplifier gain adjustment would be substituted for the high voltage adjustment.

3.6.1 SYNCHRONOUS DETECTION

The modulated outputs of the polychromator corresponding to the four wavelengths being analyzed are simultaneously measured by the photomultiplier. The ac photomultiplier output is amplified and demodulated by four synchronous demodulators corresponding to the four wavelengths being analyzed. Each demodulator is synchronized to an individual tuning fork modulator by applying the fork drive signal to the modulator reference input. The demodulator output can be approximated by the algebraic product of its input and excitation signals where the excitation is a constant-amplitude square wave.

Using a Fourier expansion for the square wave, it can be shown that a sinusoidal input of the same frequency as the excitation produces a dc level plus a series of ac components in the output. The ac components arise from the cross products of the reference signal fundamental and

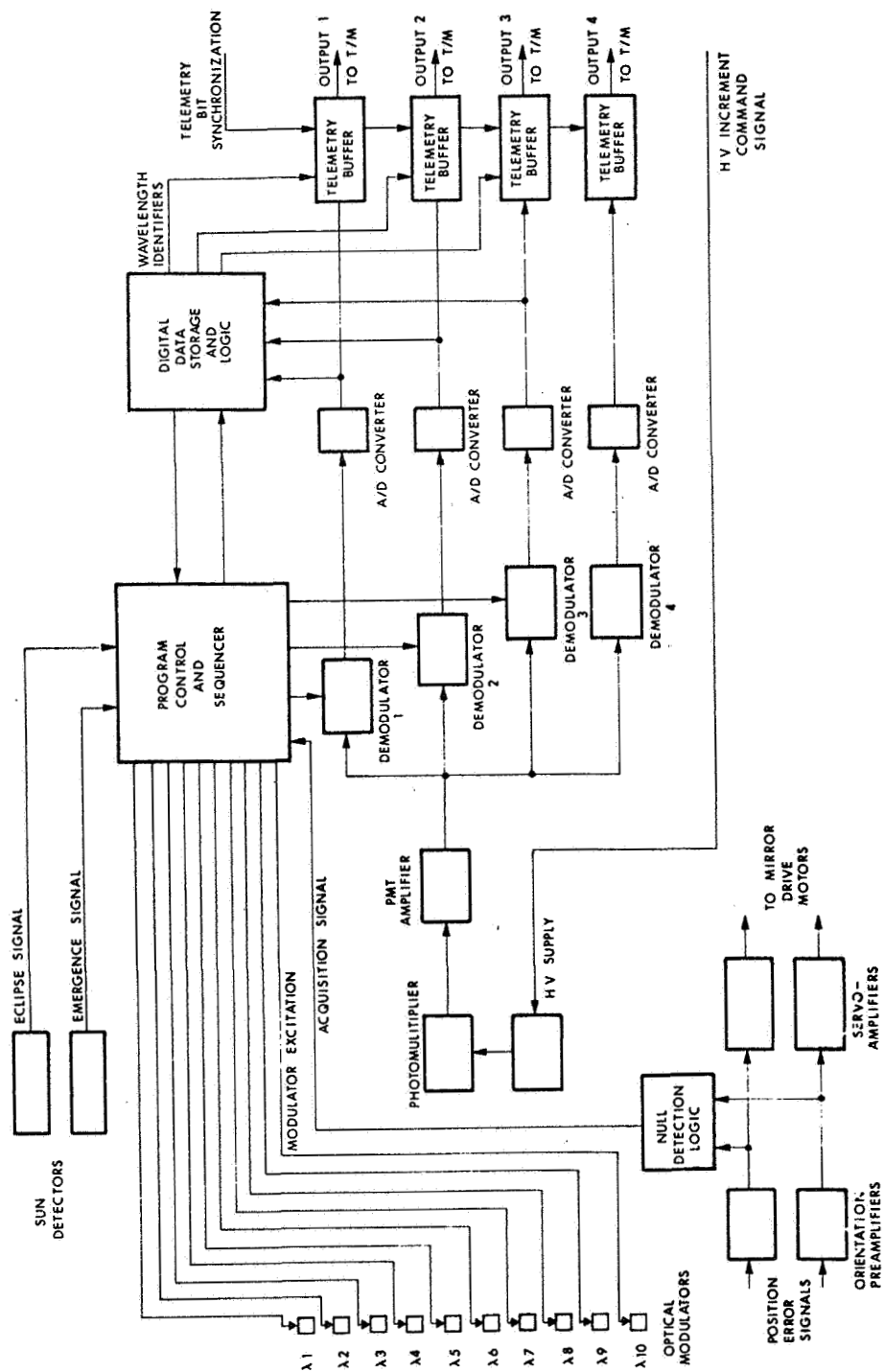


Figure 3-14. System Electronics Block Diagram

harmonic components and the fundamental of the input. Since the square wave contains only odd multiples of the fundamental frequency, and since the cross products are all sum and difference frequencies, the output contains only even harmonics of the input frequency.

In this application a low-pass filter rejects all of the output components beyond the filter cutoff frequency. The modulator frequencies must then be selected to prevent cross-coupling between channels. This cross-coupling is produced by all the cross products of input and reference signals and consists of all the sum and difference frequencies of the respective inputs. Unwanted inputs, while producing no dc output, will produce a low-frequency ac output corresponding to the difference between the input and reference frequencies. Their effects are minimized by maintaining adequate separation between the individual modulator frequencies. The cross product frequencies are then high enough to be rejected by the filter. An additional requirement on the modulator frequency selection is that there be no cross-coupling due to coincidences of their harmonics.

3.6.2 WAVELENGTH SELECTION SEQUENCE

The drive signals applied to the tuning fork modulators and the synchronous demodulators are controlled by the program control and sequencer shown in the block diagram. As described in a previous section, only three of the first nine modulators are driven at one time and the tenth modulator runs continuously. During the occultation the sequencer determines which modulators are operated and routes the respective reference signals to the demodulators. This sequence is indicated in Table 3-1.

Table 3-1 also indicates which wavelengths are measured by the respective demodulators.

TABLE 3-1
WAVELENGTH SELECTION SEQUENCE

Wavelength Group	Wavelengths Modulated	Wavelengths Demodulated		
		Demodulator 1	Demodulator 2	Demodulator 3
1	$\lambda_1 \lambda_2 \lambda_3$	λ_1	λ_2	λ_3
2	$\lambda_2 \lambda_3 \lambda_4$	λ_4	λ_2	λ_3
3	$\lambda_3 \lambda_4 \lambda_5$	λ_4	λ_5	λ_3
4	$\lambda_4 \lambda_5 \lambda_6$	λ_4	λ_5	λ_6
5	$\lambda_5 \lambda_6 \lambda_7$	λ_7	λ_5	λ_6
6	$\lambda_6 \lambda_7 \lambda_8$	λ_7	λ_8	λ_6
7	$\lambda_7 \lambda_8 \lambda_9$	λ_7	λ_8	λ_9

As the spacecraft enters the shadow, the sequencer starts with wavelength group 1 and progresses through group 7. On emergence, the sequence is reversed, starting with group 7 and ending with group 1. The direction of the sequence is controlled by the eclipse and emergence signals, and the advancing through the sequence is controlled by the data storage and logic section. An acquisition signal from the orientation system indicates that the system has completed solar acquisition and enables the initiation of measurements.

The four demodulator outputs are filtered and digitized by the four analog-to-digital converters. The digital signals are stored in the telemetry buffers to await their serial transfer to the telemetry system. The digital outputs are also routed to the digital data storage and logic section for control of the wavelength sequence.

3.6.3 SEQUENCE CONTROL

As the spacecraft approaches the earth's shadow, sunlight entering through path 1 as shown in Fig. 3-7 illuminates a detector which produces an eclipse signal. This signal occurs as the incident sunlight passes 140 kilometers above the earth's surface and is used by the logic section to start the measurement sequence. At this altitude the sunlight is essentially unattenuated by the atmosphere and the measured intensity is used in computing atmospheric transmission. The measurement sequence begins with the instrument measuring the three wavelengths of group 1 of Table 3-1. The data are digitized, stored in the data storage section, and transmitted to telemetry. At the completion of the telemetry sample the logic signals the sequencer to advance to group 2 and again store and transmit the data. This sequence continues through group 7, until all wavelength bands have been measured. This process is synchronized with the telemetry sampling which samples one wavelength group per second. Thus the complete scan requires 7 seconds, during which time the transmitted ray altitude descends from 140 to about 113 kilometers. Upon completion of this scan, the sequencer returns to wavelength group 1 and the logic switches to an adaptive mode.

In this adaptive mode the digital logic section monitors a selected digital intensity signal and compares it to its corresponding value stored in the system. The logic then senses the atmospheric transmission in a single wavelength. As the transmission reaches a predetermined limit, the logic signals the sequencer to select the next wavelength group and monitors the transmission at a new wavelength. The wavelengths monitored and the approximate switching levels are shown in Table 3-2 for both the eclipse and emergence sequences.

At the end of the emergence sequence the unattenuated solar radiation is again measured for use in the transmission computations. This sequence begins when the transmission of λ_2 increases to 75%. At this point the

TABLE 3-2

AUTOMATIC SEQUENCING LOGIC

Sequence Direction	Group	Wavelengths Telemetered	Wavelengths Monitored	Demodulator Monitored	Switching Level % Transmission
Eclipse	1	$\lambda_1 \lambda_2 \lambda_3$	λ_1	1	10
	2	$\lambda_2 \lambda_3 \lambda_4$	λ_2	2	10
	3	$\lambda_3 \lambda_4 \lambda_5$	λ_3	3	10
	4	$\lambda_4 \lambda_5 \lambda_6$	λ_4	1	10
	5	$\lambda_5 \lambda_6 \lambda_7$	λ_5	2	10
	6	$\lambda_6 \lambda_7 \lambda_8$	λ_6	3	10
	7	$\lambda_7 \lambda_8 \lambda_9$	λ_7		
Emergence	7	$\lambda_7 \lambda_8 \lambda_9$	λ_8	2	75
	6	$\lambda_6 \lambda_7 \lambda_8$	λ_7	1	75
	5	$\lambda_5 \lambda_6 \lambda_7$	λ_6	3	75
	4	$\lambda_4 \lambda_5 \lambda_6$	λ_5	2	75
	3	$\lambda_3 \lambda_4 \lambda_5$	λ_4	1	75
	2	$\lambda_2 \lambda_3 \lambda_4$	λ_3	3	75
	1	$\lambda_1 \lambda_2 \lambda_3$	λ_2	2	75

transmission of all wavelengths longer than λ_2 is greater than 75% and that of the longest wavelengths is nearly 100%. The measurement sequence begins with group 7, since this group is nearest to 100% transmission. The sequence then progresses in decreasing group order, synchronized with telemetry sampling in the same manner as in the pre-eclipse sequence. By the time this sequence reaches group 1, the transmitted ray altitude has ascended 27 kilometers above the point where λ_2 transmission was 75%. At this point the transmission of λ_1 should be suitably close to 100%. This completes the measurement sequence.

Signals from the sequencer indicate the group being measured and the direction of the sequence, thus enabling the logic section to select the proper signal for monitoring and to identify the telemetry outputs.

3.6.4 SENSITIVITY ADJUSTMENT

A high voltage increment command is used to adjust the system sensitivity via ground commands. This function is not intended as a calibration, since the system measures transmission directly, but it serves to maintain the measured intensity at a level consistent with the dynamic range of the instrument. It is expected that this command will be required to compensate for photomultiplier aging and optics degradation and will be used very infrequently.

3.7 SPACECRAFT INTERFACE

3.7.1 MECHANICAL

It is assumed that the Nimbus E spacecraft will accommodate an extended Nimbus bay module similar to that available for packaging the Nimbus D Background Ultraviolet Instrument. Preliminary mechanical layouts indicate that such a module measuring 6 x 8 x 19 inches is ideally suited for this instrument. The instrument should be located in the sensory ring at a location 90° from the pitch axis. An additional $\frac{1}{4}$ over 0" 6 x 8 x 6.5-inch module in an adjacent bay would be required for the system electronics.

The combined weight of the modules and their interconnecting cable is estimated at 16.0 pounds.

3.7.2 POWER

The maximum power consumption of the instrument is estimated at 11.5 watts. This load occurs for 60 seconds, twice per orbit. The standby power at all other times is 4.0 watts.

3.7.3 TELEMETRY

The instrument produces an output for telemetry during a 36-second interval, two intervals per orbit. The telemetry requirement is four 10-bit digital words sampled at 1-second intervals for a total of 40 bits/second during the 36-second measurement interval.

3.7.4 DATA REQUIREMENTS

The received data should be printed in a digital format and identified with the GMT corresponding to each data value. Orbital data corresponding to the time of the telemetry data is required to ascertain the spacecraft position corresponding to each data value to an accuracy of ± 1 kilometer.

3.8 CONCLUSION

The design analyses show that an instrument of the type described briefly above could readily meet, and probably surpass, all of the performance requirements. Because of the high sensitivity of the photoelectric detectors and the high irradiance values of the sunlight in the middle ultraviolet, signal-to-noise ratios between 10^3 and 10^4 could be achieved by this detector system while maintaining the requisite high spatial resolution (solar disk image-slicing) and high spectral resolution ($2.5\text{\AA}$ bandwidth per wavelength monitored).