NASA-CP-2362 19850014801

# Ozone Correlative Measurements Workshop

*Proceedings of a Workshop held at*
*NASA Goddard Space Flight Center*
*Greenbelt, Maryland*
*November 16-18, 1983*

NASA

# Ozone Correlative Measurements Workshop

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**N/\S/\**

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

**1985**

# Preface

Within NASA, the Upper Atmosphere Research Program is responsible for an assessment of possible anthropogenic influences on the upper atmosphere, particularly on stratospheric ozone. This assessment involves the conduct of a major research program which includes theoretical and experimental investigations of the upper atmosphere. NASA has been making ozone observations since the late 1960s using aircraft, balloons, rockets and satellites, while NOAA has conducted research in balloon and ground-based ozone observations and has now embarked on a long term ozone measurements program with the Tiros-N satellite series and an upgrade of the ground observing network. Ozone observations are also being conducted by universities and agencies throughout the world.

The need to observe ozone over a long term (10-20 years) to detect a small trend, places a new and difficult requirement on observational and data extraction capabilities. Satellite measurements provide a global picture, while ground-based (balloons, rockets, etc.) observations provide detailed vertical structure. It is hoped that ground data will also provide a measure of the accuracy of the satellite data. Attempts to validate the satellite observations using "ground truth" or "correlative" measurements have not, to date, been adequate because of limitations in their accuracy and precision.

Goddard Space Flight Center convened this Workshop in November 1983 to deal specifically with this problem, that is, how do our observational capabilities compare with the scientific requirements? Forty-five scientific investigators from four NASA Centers, three NOAA services, the FAA, EPA, five universities, and from organizations in Brazil, Canada, France, and Germany were invited to participate. The list of attendees appears in Appendix C. The Workshop resulted in a set of recommendations for validation of the satellite data and this report presents a summary of that meeting. It has been reviewed by most of the participants and represents the consensus reached at the end of the Workshop. It is hoped that the recommendations will serve as a strategy for programmatic planning by both NASA and NOAA and a guide for the national and international scientific community.

The Workshop was planned and organized by Goddard Space Flight Center. The assistance of the members of the Laboratory for Planetary Atmospheres is sincerely appreciated. I thank Edith Reed for her meticulous review of the manuscript and Roberta Duffy for her review and typing of the manuscript. I would also like to thank the Office of Environment and Energy of the Federal Aviation Administration for their support of this Workshop. The organizational and editing assistance of Flo Ormond of ORI, Inc. is greatly appreciated.

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Ozone Correlative Measurements Workshop

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# I. INTRODUCTION

An understanding of the variability of global ozone has become increasingly important because of its relevance to life on Earth, since the ozone overburden controls the amount of incident near-ultraviolet solar radiation reaching the Earth's surface. Ozone may also play a significant role in climate because of its strong radiative properties in the stratosphere and troposphere. A goal of NASA's Upper Atmosphere Research Program is to understand the physics, chemistry, and transport processes in the upper atmosphere and to accurately assess possible perturbations caused by natural phemomena and man's activities. Consequently, one of the primary scientific objectives in upper atmospheric research is to evaluate possible long term changes in the distribution of atmospheric ozone and their causes.

Satellite observations provide global ozone data used to describe the seasonal, latitudinal, and synoptic variations. These observations are scientifically important when employed with theoretical models to understand the transport and photochemical processes of the atmosphere. Seasonal, latitudinal, and synoptic ozone variations are also important in evaluating the longer term natural and anthropogenic changes. (Taken together, these longer term changes are called "trends".) Shorter term variations, while representing the complexity of the atmosphere, also comprise a large noise level superimposed on the long term trend. In fact, the shorter term variations are an order of magnitude higher than the expected trend, where the predicted trend for ozone at 40 km due to anthropogenic perturbations is about 5% over a ten year period.

Confirmation of a long term trend in stratospheric ozone would be of considerable scientific importance. Clearly then, long term satellite observations of ozone, with sufficient accuracy to detect a trend, are required along with a research program to study atmospheric processes. The basis for a long term monitoring program is being established. Improvements are being made to the ground-based Dobson and Umkehr observations, balloon and rocket sounding techniques are being developed and evaluated for accuracies better than 5% and precisions of the order of 1-2%. The Solar Backscatter Ultraviolet (SBUV) experiment on Nimbus-7 is now in its sixth year of operation. The National Oceanographic and Atmospheric Administration (NOAA) Tiros-N satellite series will incorporate SBUV ozone sounders. However, experience has shown that the major weakness of a long term measurement program is the inability to verify the satellite ozone profile data and to separate drifts in the instrument sensitivity from geophysical changes. Attempts to correct satellite instrument drifts with available ground-based, balloon, and rocket systems to the tolerance required for ozone trend detection have not been successful.

On November 16, 17, and 18, 1983, an ozone measurement workshop was held at NASA's Goddard Space Flight Center to discuss means to verify the accuracy, precision, and long-term stability of SBUV ozone sounders to be flown on the first Tiros-N (NOAA-F), and subsequent NOAA spacecraft carrying SBUVs into the 1990s. The emphasis of this report is the verification of the observations of the vertical distribution of ozone and not so much the column amount.

The workshop was organized around four topics. The first three relate to present ozone theory and observations. The fourth topic was the major goal of the workshop. The topics were:

1. Identify the scientific requirements for detecting trends and climatological studies.
2. Review the capabilities (and limitations) of the satellite observations.

3. Review the capability of existing correlative measurement techniques; e.g., Dobson Umkehr, absorption photometers (ROCOZ) on rockets, in situ UV photometers on balloons, Lidar and a Shuttle-borne SBUV.
4. Formulate the role of the correlative ozone measurements.

Investigators from government agencies, universities, and other nations with experience in the above areas were invited to participate in the Workshop. William DeMore, at NASA Headquarters from the Jet Propulsion Laboratory, was the overall discussion chairman. Richard Stolarski and John Frederick from Goddard Space Flight Center, Alvin J. Miller from the National Meteorological Center, and Rumen Bojkov from the Canadian Atmospheric Environment Service organized position papers for the first three topics. These position papers were distributed to each participant during the Workshop and were discussed spearately in each group as they met for about a day and a half. The positions were also discussed by the entire group to provide feedback between the subgroups. The final positions are published in their entirety as three chapters of this report.

Towards the end of the Workshop, Robert Watson and William DeMore of NASA Headquarters and the three topic chairmen met with key individuals in an executive session to develop recommendations, which were presented to the entire group and discussed further. The final conclusions and recommendations arrived at by the Workshop are given in Section III. In general, these conclusions and recommendations represented a consensus of the attendees with some controversy. One important controversy centered on whether Umkehr observations and operational balloon sondes are adequate for validation of satellite ozone profiles.

Appendices A and B deal with precision and frequency of measurements needed to validate SBUV retrievals and to independently verify an ozone trend at a given location. They provide guidelines for conducting measurements for these purposes; however, they were not discussed in detail during the Workshop period. The analyses appearing in these appendices were developed by John Frederick with comments from A. J. Miller, G. Reinsel, and P. Bloomfield.

This report is intended to serve as an advisory document for NASA for planning its ozone measurement program. Some of the recommended activities are already underway with support by the NASA, NOAA, the Environmental Protection Agency (EPA), the Federal Aviation Administration (FAA), and the Chemical Manufacturers Association (CMA), and by numerous groups in other nations which are coordinated by the World Meteorological Organization (WMO). It is hoped that the recommendations from the Workshop will also serve as a focus for a long term observation program for these agencies and the scientific community as a whole.

## II. SUMMARY OF CHAPTERS

The three chapters in this report deal with the scientific needs for ozone observations, the satellite capabilities and the capabilities of the correlative measurements. A correlative measurement is defined here as an independent ozone measurement used to validate the satellite observations or the conclusions derived from these observations. The chapters are summarized here along with some of the rationale that led to the recommendations concerning correlative measurements. The emphasis is on verification of ozone profiles rather than total column amount.

Validation of satellite data can be broken into two steps. One deals with instrument performance and the second with the inversion algorithm. The major obstacles in detecting and interpreting ozone trends from BUV observations are the uncertainties in the instrument performance

and the solar irradiance with the passage of time. A model, discussed in Chapter II, of the Nimbus-7 SBUV instrument degradation for the first four years of operation has been developed using the satellite data itself. Considering all factors of instrument performance, the measurement errors may be known to 2-3% for the 4 years. This does not meet the minimum scientific requirement as outlined in Chapter I to isolate a decrease in ozone of 0.4% per year near 40 km over a 10-year observing period. Therefore, a continuous independent check of the satellite instrument performance is considered essential.

The recommendations include verification of the SBUV measurement up to 55 km, well above the altitude where an ozone trend due to anthropogenic activity would have its maximum value. This implies the need for rocket observations or other techniques such as ground based lidar or microwave observations. Balloons can be used up to 42 km. The need for validation up to 55 km is twofold: first, to verify that the algorithm is operating properly over the entire altitude range, and second, to separate ozone trends due to anthropogenic effects from those due to solar cycle causes, since the latter would occur mostly above 40 km according to our current understanding.

The Workshop did not deal with the number of flights, sites, accuracy, cost tradeoff, etc. in detail. However, a procedure to calculate the number of flights needed vs the magnitude of random errors to specify the systematic bias between measurement systems to a certain tolerance appears in Appendix A. In that analysis, for example, 69-165 correlative measurements with a precision of 3% were needed to achieve a 1% ($2\sigma$) tolerance. It would be desirable to conduct these measurements as closely spaced in time as possible to avoid seasonal variations in the systematic biases.

The question of how the satellite trend results could be independently verified with a non-satellite set of observations was only briefly discussed but was considered essential by the Workshop participants. One approach to this problem appears in Appendix B. In that analysis the variables include the duration of the measurement period, allowable error in trend detection and several random error components including measurement precision, where the ground measurement drift is assumed to be zero over the entire period. For example near 40 km altitude at mid-latitudes, if the tolerable error in trend detection is 0.1% per year ($2\sigma$) and the precision of the instrument is ±3%, then 1800 measurements are required over a 9.9 year period to verify the local trend over a single location. This corresponds to one measurement every two days. These results are very sensitive to the time interval between consecutive measurements. As the duration of the program increases, the total number of measurements required for trend detection decreases dramatically. With the above $2\sigma$ tolerance and instrument precision, trend detection could also be accomplished with 429 measurements spread over 16.4 years or 123 measurements over 30.4 years. If the tolerable trend uncertainty were expanded to 0.4% per year, the measurement requirements would change to any of the following: 715 measurements over 3.9 years; 170 measurements over 6.5 years, or; 49 measurements over 12.0 years.

The precision and accuracy needed for ozone observations to study atmospheric processes are also discussed in Chapter I. These requirements represent estimates based on order of magnitude scaling arguments and not the result of rigorous assessments. These requirements are sorted in this Chapter by the needs for transport and chemical investigations in terms of horizontal and vertical resolution and precision. In general, the SBUV capability is adequate with regard to spatial resolution. Specifically, planetary wave number 6 which requires a longitudinal resolution of

about 30° can be resolved with a nadir viewing instrument on a polar orbiting satellite. Spatial precision, as defined in Chapter I, of a few percent to detect differences in temperature dependent chemical mechanisms which may be latitude or longitude dependent, can be resolved with the expected SBUV capability.

The vertical resolution and precision of SBUV meets the requirement for studying atmospheric processes as stated in Chapter 1. The agreement of SBUV derived ozone profiles with ozone data from balloon, rocket, and Umkehr data is shown in Chapter 2. For example, SBUV observations track seasonal variations over a particular site to within 5-20% of the ground measurement at that site. These differences are primarily due to imprecision of the ground measurement, poor intercalibration among the sites and to the coarse altitude and spatial resolution of the SBUV. The comparability must be improved, however, if interannual changes in ozone amounts are to be precisely evaluated—an important first step in detecting trends. An indication of the need for intercalibration of ground systems is the variation of individual station biases detected when the SBUV is compared with various ground systems as discussed in Chapter 2.

For the lower stratosphere (<25 km) and troposphere, the predicted ozone trends are highly uncertain. SBUV information is limited in the lower stratosphere and is practically nonexistent in the troposphere. However, if the SBUV data were shown to be valid in the lower stratosphere the benefits would be significant. A judicious application of a correlative measurement and a theoretical evaluation program could be used to evaluate SBUV results in this region. An accurate global climatology of lower stratospheric and tropospheric ozone would be very useful in a number of scientific investigations.

Chapter 3 deals with the capabilities of the ground-based, balloon, rocket and shuttle observations. Some examples of comparisons of these measurements with satellite data appear in Chapter 2. It can be concluded that at the present time no system can be considered truly operational for validating derived ozone profiles. However, several programs are now underway to improve these systems. Selected Dobson and Umkehr stations will be intercalibrated on a regular basis. The Umkehr algorithm is being improved and will take aerosols into account. The electrochemical sondes have an accuracy and precision of 5-10% between 16-26 km, increasing to 15% and more outside this range. The performance of these instruments is dependent on the care taken in their preparation.

In situ UV absorption photometers are now being developed and flown on large balloons. These instruments have high precision (1-3%) and can have high accuracy when wall losses are eliminated or accounted for properly. The highest practical altitude is 45 km. A cryopumped mass spectrometer can be used above 45 km successfully but the altitude achieved depends on balloon performance which is routinely about 42 km. Rocket measurements are presently the only practical means for obtaining data above 45 km. The ROCOZ, a solar UV absorption filter photometer, has been being improved and tests show 4% repeatability. Because of its cost, however, this system will not be available after 1986 for routine comparisons. Intercomparisons of the instruments, which are now being conducted, are an important tool for understanding our capabilities for ozone observations. Lidar and possibly microwave ground based observations presently under development may provide an alternative to expensive rocket systems for acquiring a long term data base to validate satellite observations and perform independent detection of trends.

Another correlative measurement is the proposed Shuttle-borne SBUV. This concept involves a direct comparison of the satellite measured ultraviolet albedo used in deriving ozone with those from the same type of instrument flown on the Space Shuttle. The Shuttle instrument would be carefully calibrated in the laboratory before and after each flight. The Shuttle instrument can also provide a cross check of the satellite solar irradiance measurement. The SAGE II satellite aerosol and ozone observations will also provide independent ozone data from space to compare with SBUV.

## III.    CONCLUSIONS AND RECOMMENDATIONS

The Workshop came to two major conclusions and the recommendations follow from these conclusions. The first, A, is that the validation of satellite data is a two step process involving calibration of the instrument and verification of the inversion algorithm. The second conclusion, B, is that the *results*, i.e., long term trends derived from satellite data, must be independently verified.

### A.    Validation Requirements

Validation of SBUV/2 satellite observations has two logical components, instrument performance and algorithm verification. One without the other is inadequate, nor can they be combined. The first must be done on a regular basis and involves periodic checking, correcting, and establishing continuity of the SBUV's instrument performance on the Tiros-N series, while the second algorithm verification may only be needed initially if the atmosphere's radiative characteristics do not change.

(1)    Instrument Performance Verification

SBUV/2 ozone values are derived from measurements of the Earth's ultraviolet albedo which is the ratio of backscattered radiance measured while viewing the Earth to the solar irradiance observed using a diffuser plate to scatter sunlight into the instrument field of view. However, the on-board solar observing diffuser plate may degrade with time.

      a.  The SBUV/2 containing an on-board calibration which is designed to track the long term degradation of the diffuser should be fully employed. However, this is a new technique and has never been flown before.

      b.  Instrument performance may be evaluated during periods when two NOAA SBUV/2s are in orbit. Overlap of the SBUV/2s is not a planned requirement of the NOAA operations, but should receive increased priority.

      c.  The procedures in a. and b. above are unproven and subject to single point failures. Therefore, it is recommended that a Shuttle-borne SBUV be flown periodically to provide redundancy to the above and to ensure a high probability that instrument degradation may be removed from any observed trend. The Shuttle SBUV can also be used to provide an absolute calibration of the satellite solar irradiance measurement for which there is no on-board check.

(2)    Algorithm Verification

      a.  It is essential that there be continuous monitoring of the distribution and characteristics of stratospheric aerosols. The solar ultraviolet irradiance should be monitored. Temperatures should also be monitored to help interpret any observed ozone trend.

      b.  It is essential there there be an initial evaluation of the SBUV/2 ozone algorithm through the use of independent ozone observations. It is highly desirable that these

observations be taken at a minimum of four different latitude zones. The number and precision of measurements needed for verifying the algorithm appears in Appendix A.

   c. The observation schedule should include two seasons (winter and summer) at Northern Hemisphere high and mid-latitudes, and at least one season at equatorial and at Southern Hemisphere mid-latitudes.

   d. The SBUV ozone algorithm should be validated up to 55 km.

   e. The capability to revalidate the algorithm with independent observations must be maintained in case there is a major change in atmospheric conditions or in the SBUV instrument.

## B.   Independent Trend Detection

Detection of an ozone trend would be an important scieintific result as well as an environmental concern. Therefore, a trend detected from one observing system, e.g. satellites, should be verified by independent measurements particularly in the 35-45 km region and in the troposphere.

   (1) It is essential that observations be made to 45 km, and highly desirable that they be made to 50 km. Two observing sites at different latitudes are essential; more sites are desirable.

   (2) The analyses in Appendix B can be used as a guideline for the precision, frequency, and duration of observations needed to independently detect a trend.

   (3) Observations to establish a tropospheric ozone climatology have a very high priority.

## C.   Guidelines for Observational Improvements

In order to accomplish the above goals for satellite validation and independent trend detection the following observational improvements and analyses are recommended:

   (1) EPA, NOAA and CMA support for automating and intercalibrating several Dobson and Umkehr stations is considered essential. Data from these stations will play a major role in the satellite data validation.

   (2) Lidar observations for aerosols coincident with Umkehr observations are essential. Algorithm updates to include improved ozone cross sections are also essential.

   (3) Establishing one or two more high quality stations in the Southern Hemisphere is highly desirable.

   (4) Because ozone profiles derived from Umkehr and SBUV observations are based on similar physical principles, they are not considered wholly adequate for algorithm verification or for independent trend detection. Therefore, it is essential to conduct in situ (SBUV independent) ozone observations to 50 km. These may be a combination of balloon and rocket borne observations.

   (5) Ground-based lidar and microwave observations show great promise for regular and accurate measurements, therefore continued development is encouraged.

   (6) In situ UV absorption photometers show promise of high accuracy to altitudes near 40 km. Quality of data from the present operational electrochemical sonde above 30 km is uncertain, therefore flight and laboratory tests to determine and improve their performance are encouraged.

   (7) It is essential to intercompare large satellite data sets (BUV, SBUV, LIMS, SAGE, SME) to improve our knowledge of ozone climatology, particularly in the Southern Hemisphere and lower stratosphere.

(8) For tropospheric ozone it is essential to establish operational electrochemical soundings at regular monitoring sites such as the NOAA/Global Monitoring for Climate Change (GMCC) stations.

(9) The upcoming SAGE satellite observations are considered a "target of opportunity" and will be valuable in providing aerosol and ozone data for evaluating Umkehr observations, comparing with SBUV/2 observations, and for improving ozone climatology.

# CHAPTER I — SCIENTIFIC REQUIREMENTS FOR OZONE MEASUREMENTS

## A.    Introduction

The expected magnitude of the temporal and spatial variations in ozone associated with various geophysical phenomena provides a reference against which the required accuracy and precision of measurement systems can be established. In this way the scientific uses of the data define the measurement requirements. The approach taken is to focus on studies to be performed using ozone data over the time frame 1985 to 2000 in terms of the accuracy or precision required to address each topic.

## B.    Long Term Trends

Current photochemical model calculations predict a maximum rate of change in ozone of −0.4% per year near 40 km, arising mainly from the action of fluorocarbons. This value is nearly independent of latitude and season and has changed little as theoretical understanding has evolved over the past 10 years. Detection of a trend in the upper stratosphere involves the capability to define both the magnitude and altitude dependence of the ozone change because observed changes in ozone represent the combined actions of several causes. For example, to separate a solar cycle variation from a fluorocarbon-related trend, differences in their altitude dependence as well as temporal variations would be examined; the solar cycle behavior should be quasi-periodic while the fluorocarbon trend is likely to be more nearly linear over long time periods.

The minimum requirement for trend detection is the capability to isolate a decrease in ozone of 0.4% near 40 km per year over a 10-year period from the background atmospheric noise. The desired capability is to detect a trend of this magnitude to an accuracy possibly as high as one part in four in order to better define the trend. In statistical terms this implies that the desired 95% confidence limits on the detected trend should be ±0.1% per year over a 10-year period of data. This is a goal and may not be possible with existing measurement techniques. Predicted trends at 30 and 50 km are on the order of 0.1% per year. At these altitudes the minimum requirement is a measurement precision sufficient to detect an ozone change of 0.1% per year over the period 1985 to 2000 since better precision is not likely.

Knowledge of the variability in the ultraviolet solar irradiance, especially in the spectral region 175-225 nm, is essential if one is to attribute upper atmospheric ozone variations to this causal agent. A solar cycle change in irradiance on the order of 20% appears reasonable between 175 and 200 nm, corresponding to a mean variation in the vicinity of ±3% per year over one-half of the solar cycle. Smaller changes likely occur at wavelengths longer than 200 nm. Ozone measurements should be accompanied by observations of the ultraviolet solar irradiance which have a minimum precision capable of detecting the 175-200 nm trend to an accuracy of one part in ten over a five to six year period of data for a 95% confidence limit of ±0.3%. An even higher precision would help to separate solar-driven changes in ozone from trends related to other sources.

The above discussion concentrated on the detection of ozone trends in the upper stratosphere. However, the bulk of the total column ozone abundance resides in the lower stratosphere and potential climatic effects associated with infrared radiative transfer are related to ozone in the troposphere and the region immediately above the tropopause. Model predictions of trends in lower stratospheric ozone have varied greatly as our understanding of the relevant

chemical processes has evolved. Trend estimates have ranged from a maximum of 0.1-0.2% decrease per year in past calculations to approximately zero change or a slight increase using currently accepted chemistry. Furthermore, transport processes have a significant impact on lower stratospheric ozone and can lead to perturbations that have latitudinal variations. However, we are still relatively ignorant of the spatial structure of potential ozone changes in the lower stratosphere. A goal of trend-related ozone measurements in the lower stratosphere is to provide the capability to distinguish between the various model scenarios of predicted ozone changes. If a trend as large as 1% per decade exists, the data should have sufficient precision to detect it unambiguously. The same reasoning applies to measurements of total column ozone, which to a substantial degree reflects the lower stratospheric abundance. Thus, the minimum requirement on a measurement system here is the capability to detect an ozone trend of 0.1% per year in the lower stratosphere as well as in the total column content over a ten-year period.

In the troposphere one is likely to encounter interhemispheric differences in ozone trends and the scientific requirement here is to have the capability to identify these. A 0.1% per year trend in stratospheric ozone has approximately the same impact on the total column as would a 1% per year trend confined to the troposphere. We require, as a minimum, a measurement precision sufficient to define a trend of 0.5% per year independently in each hemisphere over ten years. To discriminate differences between the Northern and Southern Hemisphere's troposphere, the requirement for trend detection is somewhat more stringent, being 0.2-0.3% per year.

## C.   Physical Mechanisms and Climatological Studies
### 1.   Transport

Transport of ozone occurs most efficiently in the lower stratosphere but is still significant upward through the transition region from dynamical to chemical control. In the winter hemisphere this region can extend into the upper stratosphere at middle and high latitudes. Estimates of the measurement precision required can be obtained by considering the continuity equation, including only transport, for the ozone mixing ratio, $\chi$:

$$\frac{\partial \chi}{\partial t} \approx \frac{\partial}{\partial y} \overline{(v'\chi')} + \overline{w} \frac{\partial \chi}{\partial z} \tag{1}$$

where v and w are meridional and vertical velocities respectively in the y and z directions. An overbar denotes a zonal average and a prime represents the deviation from this average. Definition of a wavenumber six disturbance requires a resolution of approximately 30 degrees in longitude, and we consider the smallest eddies of interest to have an amplitude equal to 10% of the local mixing ratio, $\chi'/\chi = 0.1$. The error in the meridional derivative is related to the error in the difference $\chi'_2 - \chi'_1$ where the subscripts denote different latitudes, and we implicitly assume the meridional velocities, v , to be well known. If the uncertainty in each $\chi'$ value is $\Delta\chi'$, then the uncertainty in $\chi'_2 - \chi'_1$ is $2\Delta\chi'$ for uncorrelated errors. If we allow as much as a factor of two error in the derivative, then $2\Delta\chi' \sim \chi'_2 - \chi'_1 \sim 0.1\chi' \sim 0.01\chi$ where we assume the difference in eddy mixing ratios, $\chi'_2 - \chi'_1$ to be on the order of 10% of either value alone. We therefore require $\Delta\chi' \sim 0.005\chi$. Subject to these assumptions we require a spatial precision in the total measured mixing ratio of 0.5% over latitude scales of the order of 10 degrees. This is typical of dynamical

model grid size. The second term on the right hand side of equation 1 is poorly known because of the error associated with deducing vertical velocities. The uncertainty in the velocity is the major determinant of error in the entire term, and no strict precision requirement placed on the ozone vertical gradient would remove this problem. A 1% precision in the vertical over an atmospheric scale height is considered adequate for the evaluation of equation 1. We stress that the measurement requirements given above represent estimates based on order of magnitude scaling arguments and are not the results of a rigorous assessment.

## 2. Chemistry

In the transition region from dynamical to chemical control and above, the ozone concentration responds to temperature variations such as those that occur around latitude circles as a consequence of planetary scale wave activity. A quantitative evaluation of the temperature sensitivity of ozone and its variations with altitude, can provide information on the nature of chemical mechanisms responsible for removing odd oxygen. The scientific requirement here is that the ozone measurements have sufficient spatial precision to allow distinguishing between the temperature dependencies of the various chemical cycles. The horizontal scale of interest here is of the order of 30 degrees in longitude. On a constant pressure surface the ozone number density can be approximated by the relation:

$$[O_3(P, T)] = f(P)\, e^{A/T} \qquad (2)$$

where P and T are pressure and temperature respectively and the function f is only weakly dependent on temperature. For odd hydrogen-dominated catalytic loss we have $A \sim 500$ while for odd nitrogen $A \sim 1000$. In altitude regions where several cycles operate, A takes on intermediate values. As a science requirement we should be able to distinguish changes in ozone associated with a temperature dependence described by $\Delta A = 100$ (e.g., A = 900 from that for A = 1000) when the total temperature change is 10K. Taking the two temperatures to be 250 and 260K, we have:

$$\frac{\Delta O_3}{O_3} = \frac{e^{1000/250} - e^{1000/260}}{e^{1000/260}} = 0.166$$

for A = 1000 and:

$$\frac{\Delta O_3}{O_3} = \frac{e^{900/250} - e^{900/260)}}{e^{900/260}} = 0.149$$

for A = 900. The difference in spatial ozone variations is $0.166 - 0.149 = 0.017$. Thus, in the photochemical regime we require a spatial precision of 1-2% in ozone values to perform definitive studies of differences in chemical mechanisms.

## 3. Special Events

A variety of special atmospheric events occur on widely differing time scales that lead to variations in the ozone abundance. Stratospheric warmings and small solar proton events represent

the more frequent of these. During these events it is possible that the ozone profiles in some locations will differ substantially from those in more typical atmospheric conditions. Correlative measurements here would help to establish the accuracy of the satellite retrievals in circumstances where the first guess profiles used in inversion algorithms are far from the true condition. Since we are here looking for gross variations in ozone, there is no need to place unusual requirements on the correlative measurements and precisions of order ±5% are acceptable. A major volcanic eruption with the magnitude of El Chichon appears unlikely (but nevertheless possible) in the 1985-2000 time frame. We do not deem it necessary to base any specific measurement requirements around the occurrence of such sporadic and relatively rare events.

# CHAPTER 2 — CAPABILITIES OF SATELLITE SBUV MEASUREMENTS

## A. Introduction

This section deals with capabilities of the SBUV measurement including satellite coverage, accuracy and precision. SBUV instruments were flown on two Nimbus satellites and SBUV/2 instruments will be flown on the NOAA-F (December 1984), NOAA-H (1986) and NOAA-J (1988) Satellites with the possible extension into the 1990s on the NOAA operational satellites.

## B. Coverage — Space/Time

Figure 1 depicts a typical coverage chart for one day of SBUV data in the Northern Hemisphere mid-winter. On each day there are about 13-14 orbits separated by about 27° longitude. Note that no data are obtained over the polar night region. This data coverage is for a local noon equatorial crossing time (Nimbus-7). For a local 1500 crossing time (NOAA-F), an additional 8 degrees of latitude coverage is lost in the winter hemisphere.
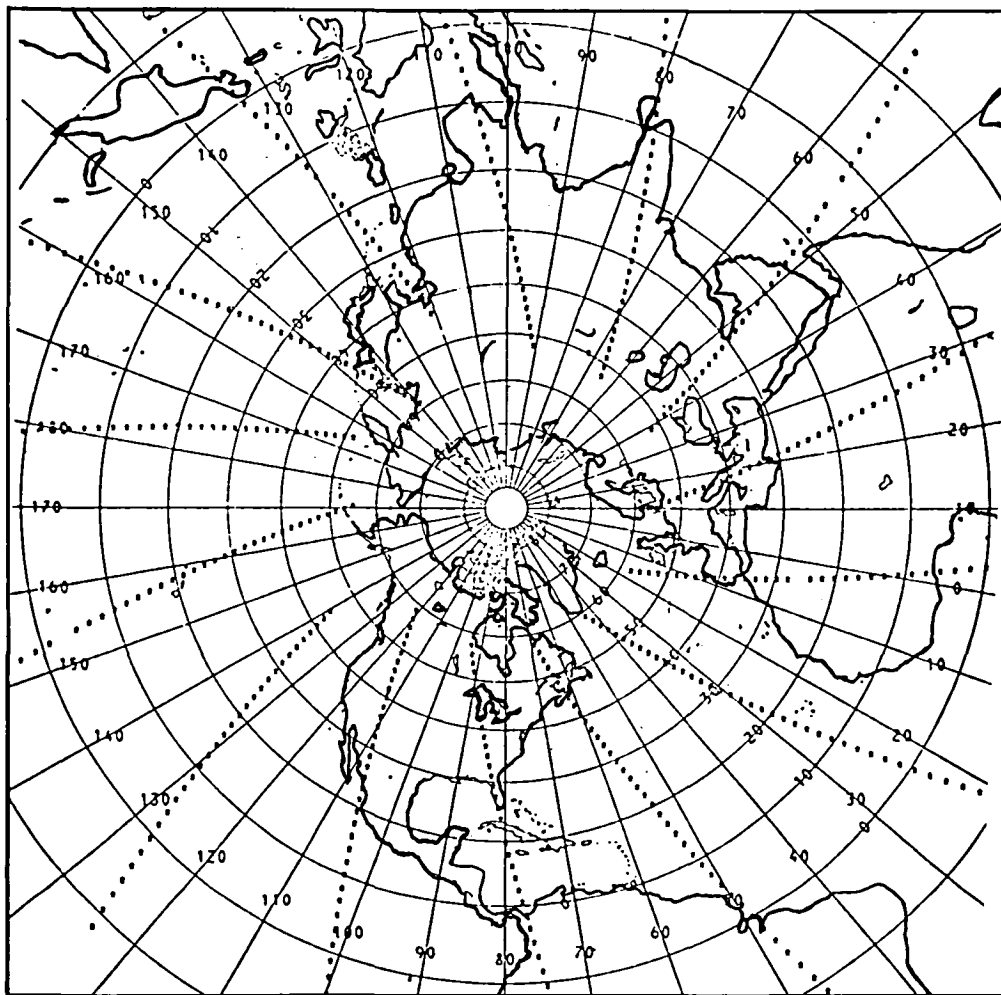


**SBUV COVERAGE FOR JAN. 5, 1979**

Figure 1.   Coverage of SBUV data in the Northern Hemisphere mid-winter, is shown by dotted lines.

The weighting functions for SBUV are presented in Figure 2. The longer wavelengths provide information on total ozone (Bhartia et al., 1983) while the shorter wavelengths are used for vertical profiles (Klenk et al., 1983). The SBUV experiment provides ozone profiles with a vertical resolution of about 8 km between 0,7 mbar and the peak of the ozone density (25 to 50 mbar). Above and below these levels the information content degrades; however, Bhartia et al. (1984b) show good agreement with mid-latitude ozone sondes in the lower stratosphere.
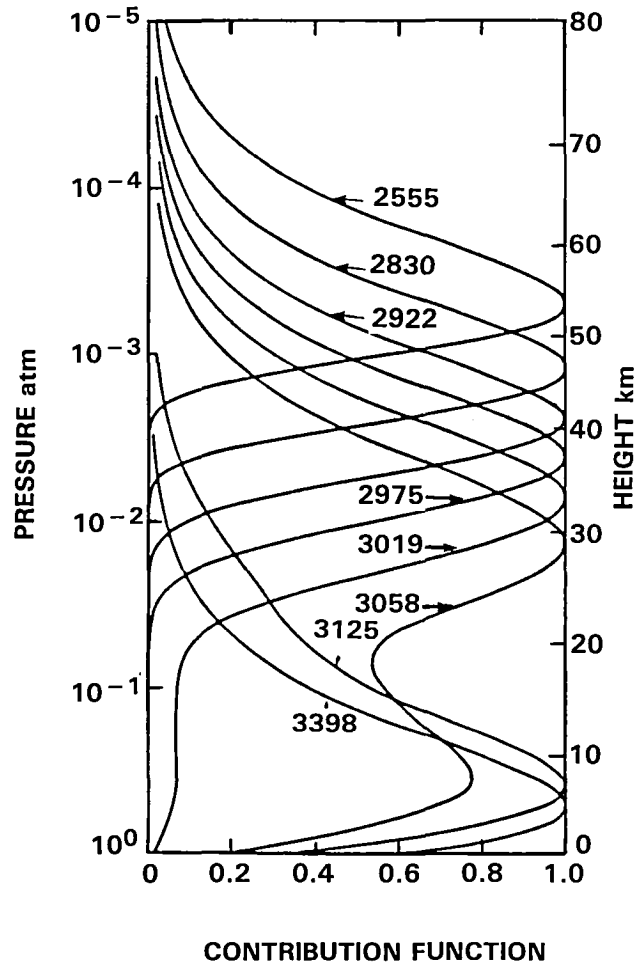


**CONTRIBUTION FUNCTION**

Figure 2.  Contributions to the Nadir direction radiance by backscattering at various levels in the atmosphere (from Mateer, 1977).

## C. Radiometric Calibration Accuracy

SBUV instruments have been designed to measure both the solar irradiance and backscattered radiance. Ozone is derived from the ratio of these two measurements. The absolute accuracy of irradiance and radiance calibration of the SBUV instrument to be flown on NOAA satellites is estimated at about 6% and 7% respectively. Most of these uncertainties are caused by uncertainty in the precise output of the ultraviolet calibration source; however, their precision and the ratio of radiance to irradiance, needed for ozone measurement, is less uncertain. The primary source of error in determining this ratio is the uncertainty in calibration of the laboratory reflectance standard ($BaSO_4$ plate) used to simulate the diffuse Earth-atmosphere scene. It is believed that with careful quality control, pre-launch accuracies of the ratio of radiance to irradiance (albedo) and precision for SBUV instruments is about 1% or better.

Reproducibility of the standards is of the order of 1% and better, therefore the precision of the albedo calibration could achieve the reproducibility of the instrument measurements which is about 1/2%. It is important to note that ground based calibrations are usually performed in static conditions with signal levels remaining relatively constant during the calibration procedures. In addition, the instrument dynamic range far exceeds the radiometric levels employed in the calibrations. Therefore, final accuracy of radiance/irradiance ratio calibration for a space environment will be determined by uncertainties in transferring pre-launch calibration values to in-orbit measurements.

## D. Instrument Degradation

Satellite instruments are subject to sensitivity changes during operation in space. Accurate assessment of the degradation is critical to the success of the experiment. However, this is not an easy task, especially in UV experiments where the current technology does not allow an onboard calibration source. Fortunately, the ozone measurement requires only a relative measurement of the backscattered radiance to the incident solar irradiance. Therefore most of the instrument effects and even the effect of the solar output variation cancel out in the ratio of the two measurements. The radiance and irradiance measurement differ since the irradiance measurement employs a diffuser which reflects sunlight into the instrument. Thus the calibration correction in the ozone measurement, due to the instrument change, is reduced to a correction for the diffuser characteristic change if the ratio of the radiance to the irradiance is obtained from nearly simultaneous measurements.

An accurate estimation of the diffuser degradation for SBUV/TOMS instruments on Nimbus-7 ' is crucial if trends are to be derived from these measurements. This estimate has been made using the following procedures. In two time periods, SBUV measured the solar flux approximately 14 times a day rather than once per day. This accelerated the degradation of the diffuser and accordingly the instrument output decreased significantly in the SBUV solar flux measurement. Figure 3 shows relative SBUV instrument output at 273.5 nm in the solar flux measurement and the accumulated exposure time of the diffuser to the Sun, which indicates a strong anti-correlation between the two variables. Based on the above fact, a model has been developed to explain the instrument output in the solar flux measurement and to estimate the diffuser degradation.
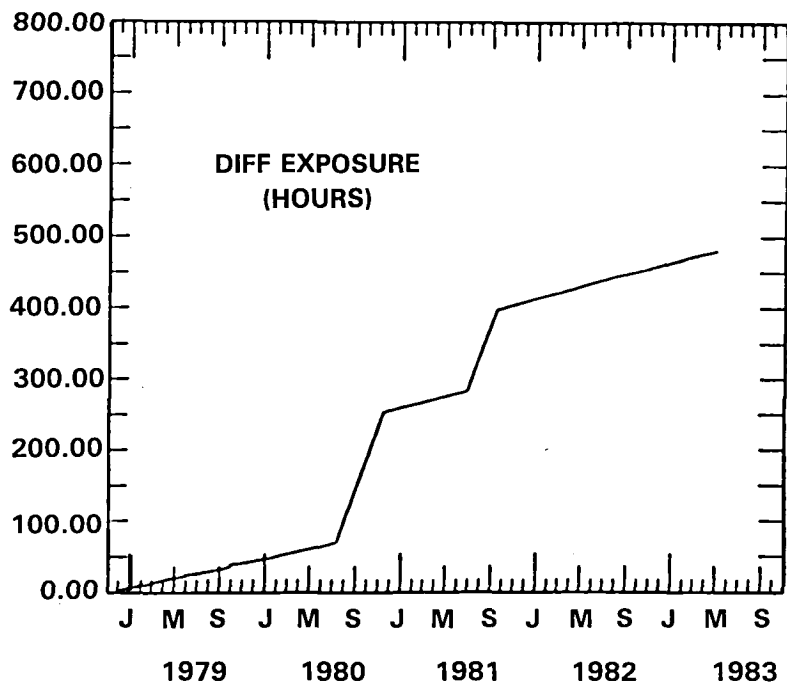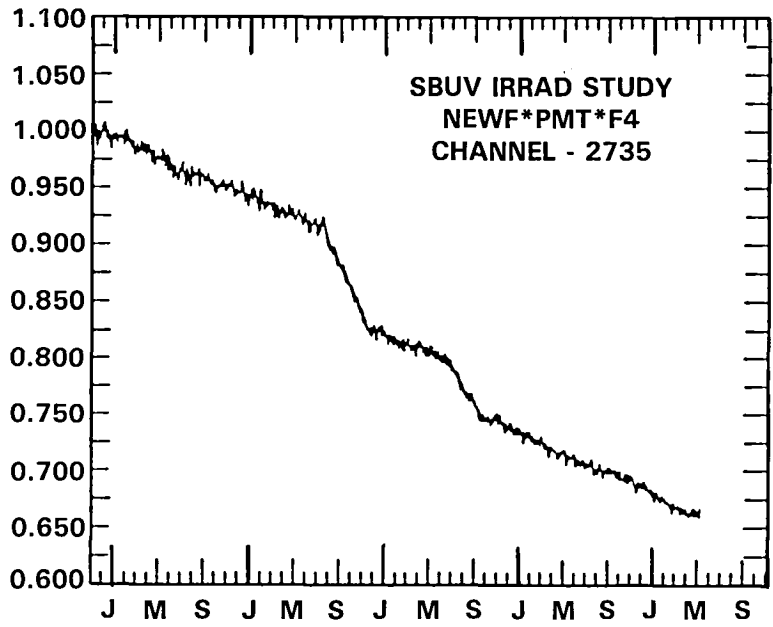
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Figure 3. The top figure shows the relative instrument output at 273.5 nm in the solar flux measurement and the bottom figure the accumulated exposure of the diffuser to the sun.

The model assumes that the instrument output change due to the diffuser degradation has an exponential form where the exponent contains constants of degradation and a time dependent function related to the diffuser exposure to the Sun. This assumption is not unreasonable based on the fact that the instrument output change due to the degradation shows an approximate exponentially decaying shape. At present, no information is available on the solar output change in the middle ultraviolet. Therefore, the model assumes that the instrument output due to the instrument degradation (excluding the diffuser) and the Sun decreases exponentially as a function of time. The final model fit has a unique functional shape as shown in Figure 3. A regression analysis of the model coefficients with four years of SBUV data for the ozone measuring wavelengths shows that:

1) 99.8% of the variance is explained by the model.
2) The standard deviation of the residue is of the order of 0.5%.
3) Standard errors of the coefficients are less than 2%.

Therefore the model explains the measured data extremely well and has been used to correct the ratio of the backscattered radiance to the incident solar irradiance for both SBUV and TOMS.

The total instrument output change due to the diffuser degradation is about 30% for four years of SUBV data. Consequently, the uncertainty of the instrument correction from the model alone for the ratio of the radiance to the irradiance is only on the order of 0.6% (at the $2\sigma$ level) for a period of four years if the model reflects the physical reality. Since there is no direct way to verify the model and its result, a few indirect ways have been used to confirm the accuracy of the instrument correction for the ratio (radiance/irradiance) measurements. A check is made for a trend in the zonal 25°S to 25°N averaged albedo at 339.8 nm where ozone absorption is weak. After four years no significant trend in the albedo at 339.8 nm has been identified even though the amount of the correction for the diffuser degradation is about 10% at this wavelength. Another check has been made by examining the trend of the minimum reflectivities of an open ocean area and a desert. It is not unreasonable to assume that the reflectivity of the open ocean or desert remains constant from one year to another. No significant change of the reflectivity has been detected.

It has to be emphasized that the above checks can be done only within limiations because of insufficient data and the uncertainty of the assumption that the geophysical variables are constant. Considering all the facts examined, it is concluded that the instrument correction of SBUV/ TOMS for the albedo measurement is probably accurate within 2-3% for the first four years of the instrument operation.

The SBUV/2 instrument for Tiros-N incorporates a mercury lamp which is designed to provide inflight traceability, through a measure of the diffuser reflectance, of the backscattered radiance to the solar irradiance ratio. The precision of this inflight check is yet to be determined; however, high internal precision may be possible.

The impact of a radiance "change" on the retrieved ozone values is shown in Figure 4 (Bhartia, personal communication) which indicates the impact of a 5% albedo error at all wavelengths on the retrieved ozone profiles at low-, mid- and high latitudes. This error has maximum impact at the upper levels and the effects are very latitude dependent. Between 4 and 1 mbar, for example, the error in latitude gradient is reversed.
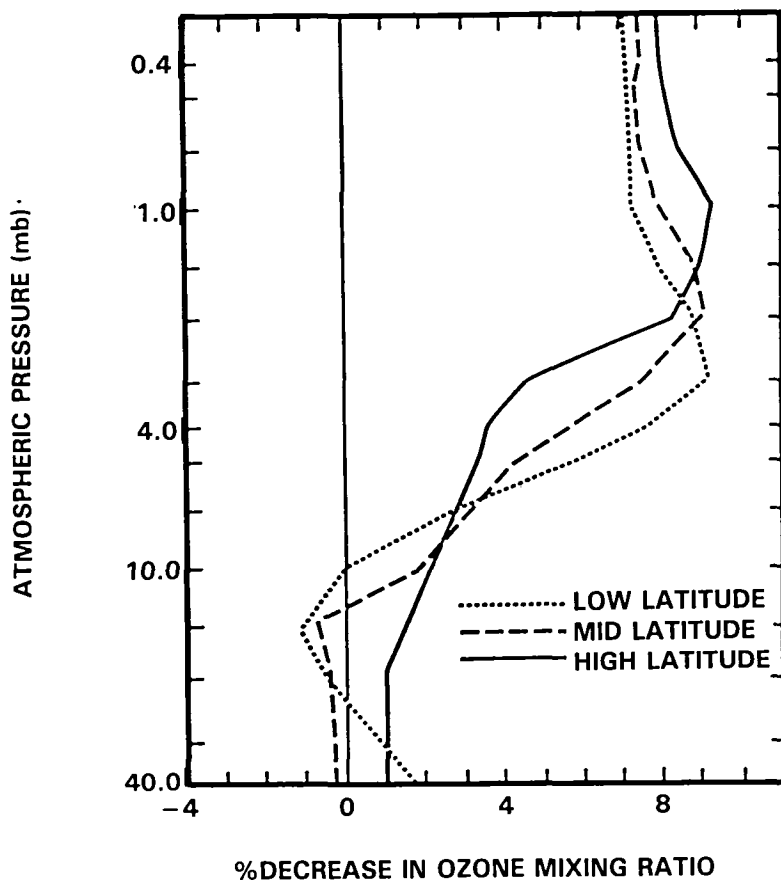
Figure 4. Effect 5%, uniform wavelength, radiance error on derived ozone mixing ratio for three latitude zones. Errors are the largest at 3 mb.

An error pattern with such characteristics is of considerable concern, not only in the error of the final products, but also in our planning of ground-truth measurements which must determine it. Clearly, it is much better to have the radiances "well calibrated" before implementation of the ozone algorithm. Algorithm performance for total ozone and ozone profile retrievals is discussed below.

E.    Algorithm Accuracy
      Total Ozone
      In the case of total ozone measurements, the basic data for comparison have been the Dobson ground-based observations. The results of such comparisons have been presented by Bhartia et al. (1984a) and the results are presented in Figure 5, plotted as a function of latitude (Northern and Southern Hemisphere combined) for the period November 1978 - December 1979). For the 58 Dobson stations the average bias is 8.3% (SBUV lower than Dobson) with a standard deviation of 2.5% and a standard deviation of the difference at a station on the order of 5%. This level of precision results from 50 satellite match-ups per station per year with a standard error estimate of 0.34%. For long-term trend estimates, errors in the Dobson instruments are assumed to be random and tend to cancel one another.

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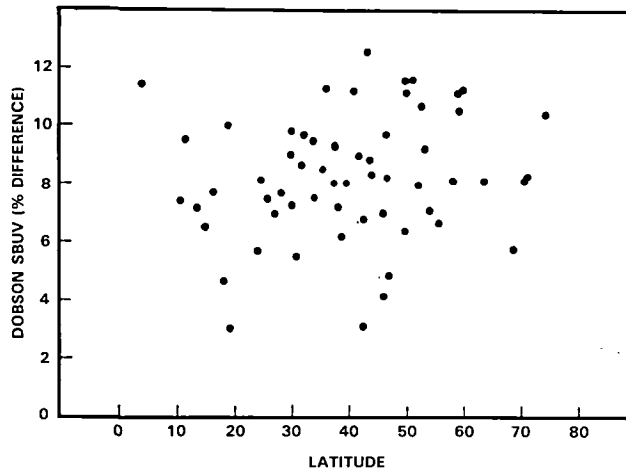
Figure 5.    Comparison of SBUV and Dobson total ozone as a function of latitude. SBUV minus Dobson for 58 stations. Northern and Southern hemisphere combined (November 1978 through December 1979).

Synoptic analysis procedures have also been utilized to compare SBUV data against other satellite products using maps as shown in Figure 6 for SBUV, TOMS, and TOVS (Tiros Operational Vertical Sounder) (example is for SBUV).  Comparisons between map products are quite favorable (e.g. Miller at al., 1979) and it appears that SBUV can depict the ozone fields at least to wave number 6.
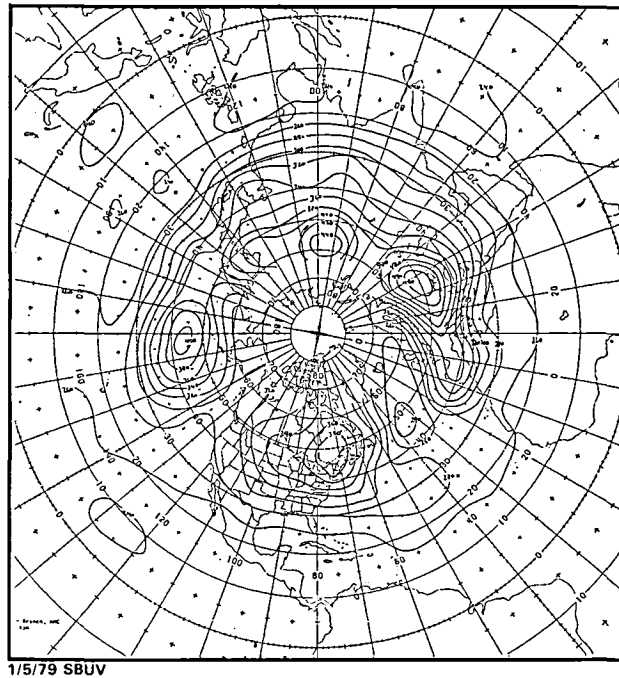


Figure 6.    Example of synoptic analysis of SBUV total ozone data which can be compared to other similarly prepared atmospheric data.

## Vertical Profiles

With the optimum statistical technique, (Rodgers, 1976) as applied in the SBUV retrieval algorithm, one end product is the solution profile covariance matrix which indicates, quanti-tatively, the precision of the retrieved profile in each layer.  The estimates of precisions of SBUV

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ozone profiles are presented in Table 1. This table also includes the standard deviation of SBUV-Umkehr and SBUV-balloonsonde comparisons for the comparable layers. Reasonable agreement (5-10 percent in the SBUV "range") is obtained between the various precisions suggesting reasonable assumptions of the instrument precisions. The observed precisions include possible seasonal variations and temperature effects on absorption coefficients used in the SBUV retrievals.

Precision estimates also depend strongly on the assumed short term atmospheric variability. Values listed should apply to data collected over one year in mid-latitudes. During summer, when day to day variability of atmospheric ozone reaches a minimum, retrieval noise may be 2 to 3 times smaller. By contrast, profiles retrieved in a highly disturbed atmosphere are likely to be more noisy.

Table 1. Estimate of Precision of SBUV Ozone Profile

| Layer | Altitude Pressure Range (mb) | Retrieval layer center (km) | Precision % layer averaged partial pressure) | % Std Dev. SBUV-Umkehr | SBUV/Balloon |
|---|---|---|---|---|---|
| 10 | .5 - 1 | 51 | 4% | - | - |
| 9 | 1 - 2 | 46 | 4 | 16 | - |
| 8 | 2 - 4 | 40 | 3 | 8 | - |
| 7 | 4 - 8 | 35 | 4 | 7 | - |
| 6 | 8 - 16 | 30 | 5 | 5 | 11 |
| 5 | 16 - 32 | 26 | 8 | 6 | 9 |
| 4 | 32 - 63 | 21 | 10 | | 10 |
| 3 | 63 - 127 | 17 | 20 | | 21 |
| 2 | 137 - 253 | 13 | 37 | | 30 |

Comparisons of the SBUV results with rocketsondes, balloons and Umkehr observations have been summarized by Bhartia et al. (1984b). Sample comparisons are shown in Figures 7, 8 and 9. In Figure 7, two optical rocketsondes (ROCOZ) (Krueger, private communication, 1984) and a balloonsonde flown on October 21, 1979 are compared with the coincident SBUV profile and with an ozonesonde profile. The rocket flights were conducted in a research mode and very carefully processed. Results show that SBUV profile data agree with the rocket and ozonesonde profiles about as well as their agreement among themselves. In Figure 8, SBUV layer 9 (0.99-1.98 mb) monthly means over Boulder are compared with Umkehr measurements made at Boulder; ratio of the two monthly means are also shown. Seasonal variations are tracked by both; however, there are differences of 5-15%. Finally, in Figure 9, SBUV layer 6 (7.9 - 15.8 mb) monthly means over Payerne, Switzerland are compared with balloon ozone soundings made there. Agreement here is better than 10%; Bhartia et al. (1984b) show similar agreement with ozonesondes down to layer 2 (127 - 253 mb).
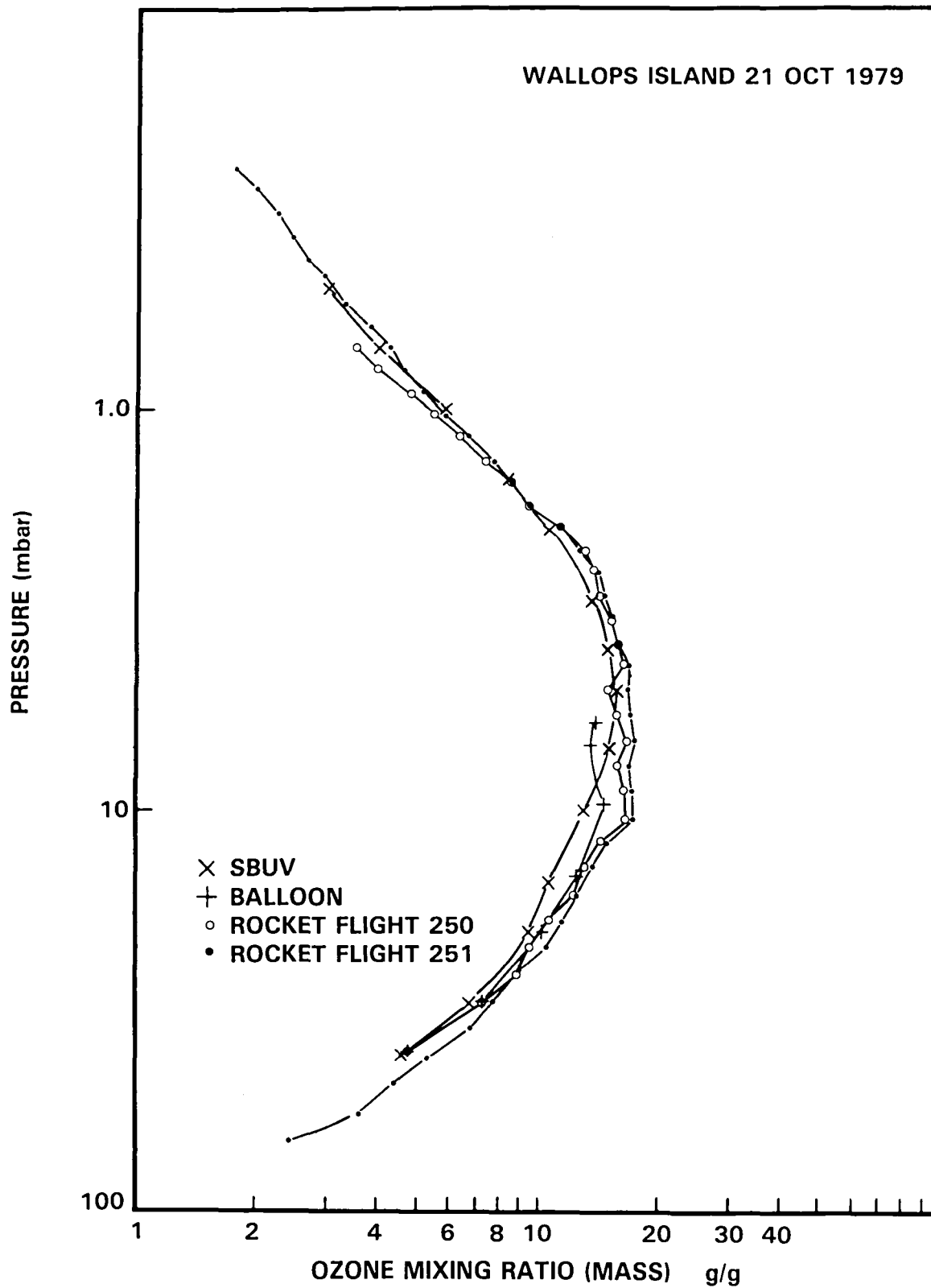
Figure 7. Comparison of rocket optical and balloon ozone sounding data with coincident SBUV satellite zone retrieval.

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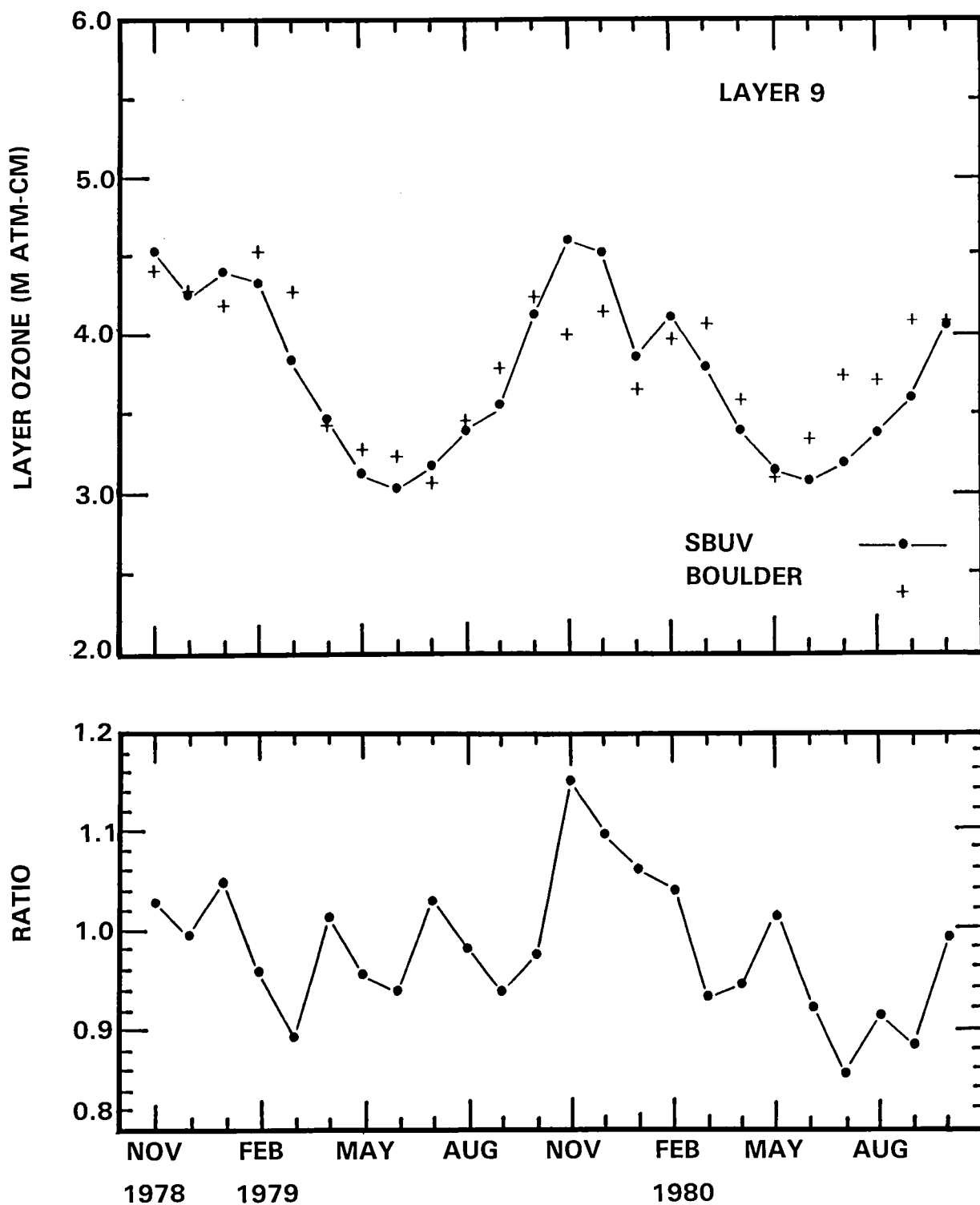
Figure 8. Monthly mean comparison of SBUV and Umkehr observations over Boulder, CO in layer 9 (1 - 2 mbar), (upper). Ratio of two data sets (SBUV/Umkehr) (lower).
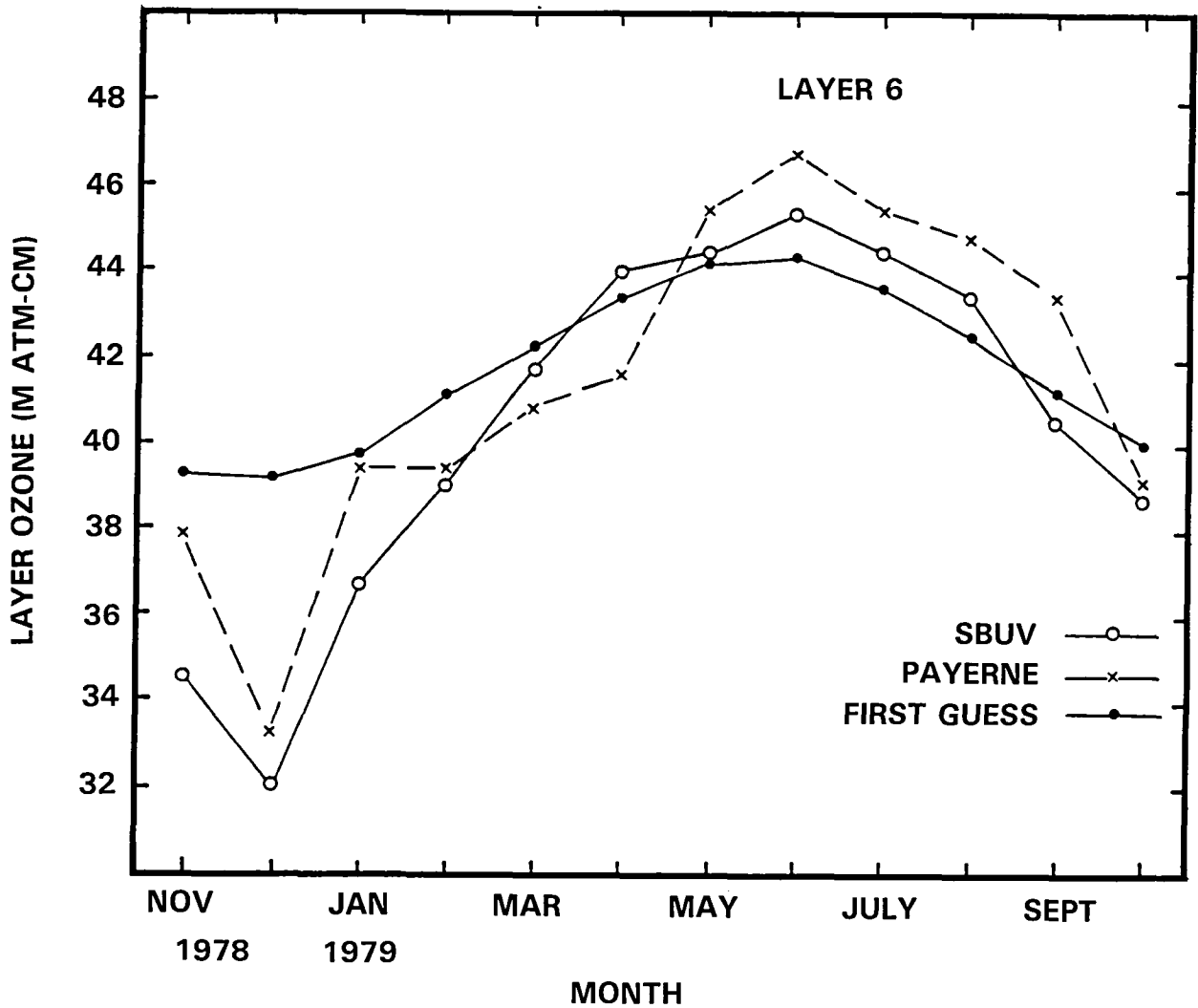
Figure 9.   Monthly mean comparisons of SBUV and Payerne Balloon ozonesondes in layer 6 (7.9 - 15.8 mbar).
Also shown are the SBUV first guess data. Particularly evident in winter months is that first guess has
little influence at this level.

Umkehr and SBUV comparisons for layers 9 to 6 for the period November 1978 - October 1979 as a function of latitude are depicted in Figure 10 (Bhartia et al.). A generally positive bias exists at the upper layers with SBUV greater and the sign reversing at the lower layers. Moreover, in layer 6 a pronounced trend with latitude exists such that SBUV is lower at the higher latitudes. Interestingly, this trend is not as apparent in layer 7. These differences are of the order of 10-20% and are systematic in altitude and latitude.
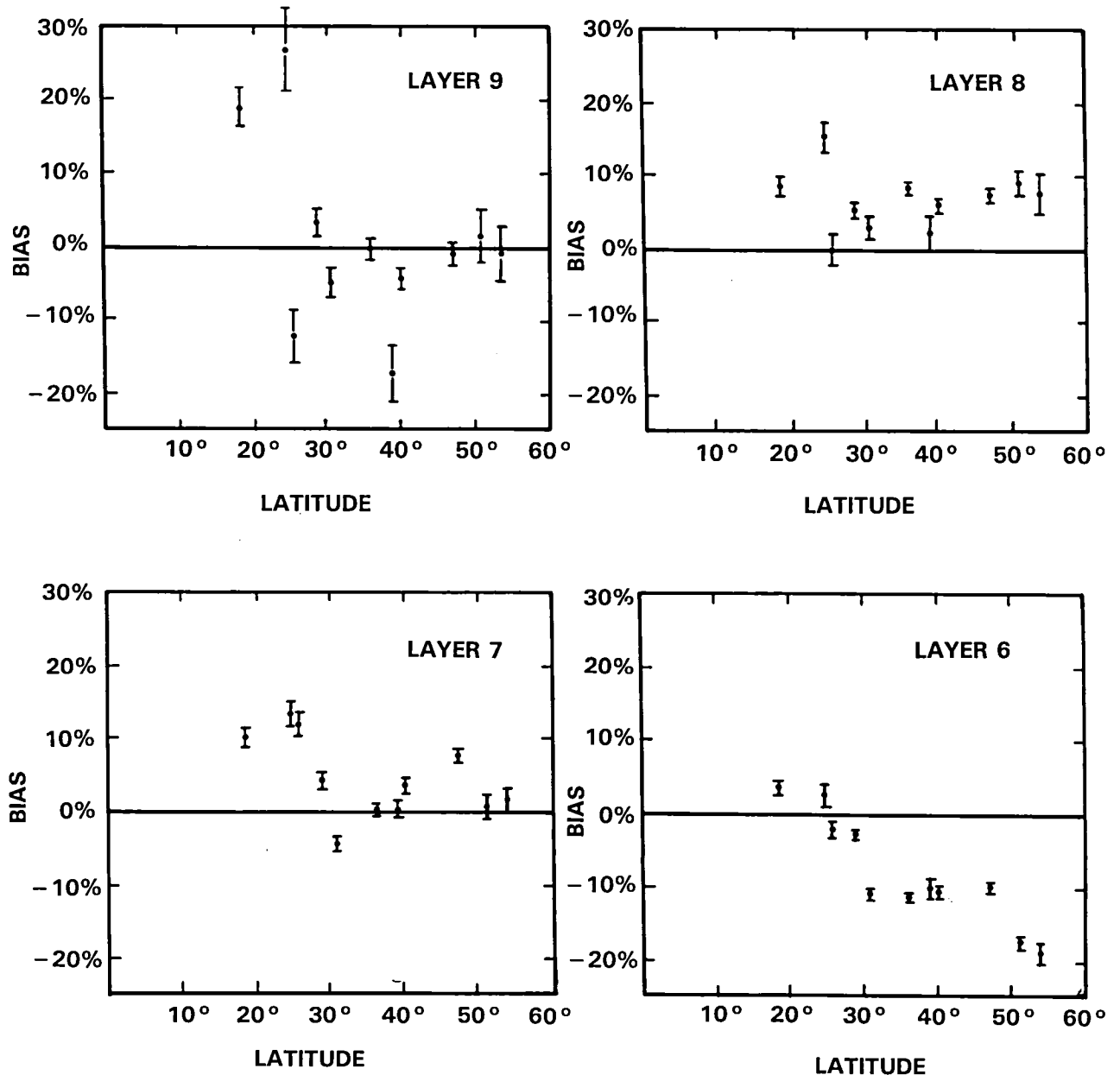


Figure 10. Comparison of monthly means between SBUV and 11 Umkehr stations (SBUV-Umkehr) in the Northern Hemisphere for the period November 1978 to October 1979.

As the last example of satellite capabilities, comparisons of the ozone synoptic analyses with ancillary data are described. Specifically, Nagatani and Miller (1984) have presented correlations of ozone mixing ratio and temperature around a latitude band. The pressure-latitude cross section of this correlation based on the monthly average fields for January 1979 is depicted in Figure 11. The general pattern of correlation is what would be expected from photochemical-dynamic considerations with large negative values at 2 and 1 mbar changing to large positive values at 30 mbar. The zero line slopes upward with latitude, also as expected. The closed zero contour at 30N and 10 mbar appears related to rawinsonde sampling problems in this area while the positive correlations at 2 and 1 mbar in northern latitudes were unanticipated. Similar comparison using LIMS data (Gille, private communication, 1983) have also indicated such patterns, corroborating this result.
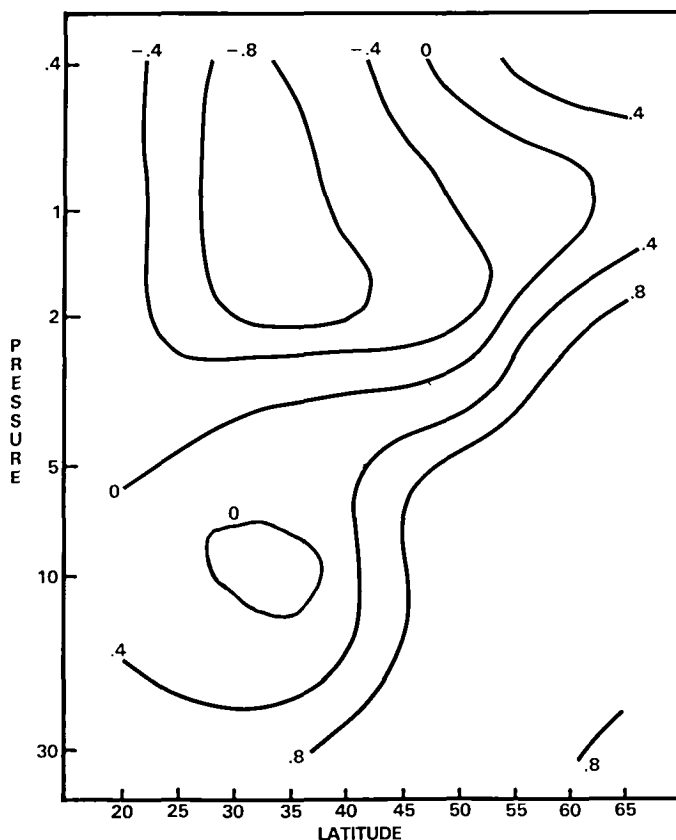
Figure 11. Correlation of ozone mixing ratio and temperature around a latitude band for the month of January.

From the recent experience with the El Chichon volcanic eruption, several considerations have emerged with regard to algorithm errors. The first is that a substantial, high altitude, injection of $SO_2$ has a significant impact on the SBUV retrievals Fortunately, it appears that the $SO_2$ reduces to $H_2SO_4$ aerosols in about a month, so that $SO_2$ absorption features are not a significant problem for long-term trend determination. The aerosols thus formed, however, do impact the backscattered component of the radiation. The present SBUV algorithm includes an aerosol detection procedure and contaminated data are flagged. It is important to recognize that aerosols below about 20 km have negligible impact on SBUV ozone results. For an aerosol layer at higher altitudes (i.e., El Chichon) the impact is mainly at the lower levels and is negligible near 40 km.

# CHAPTER 3 — CORRELATIVE OZONE MEASUREMENT CAPABILITIES

## A. Introduction

This section deals with the capabilities of ground-based total and vertical ozone distribution measurements which can be used to support satellite ozone observations. Total ozone measurements are reviewed; however, the main thrust of the discussion is on the capabilities of vertical ozone distribution measurements starting with the Umkehr method, followed by balloon-borne chemical ozonesondes, mass spectrometer beam system, in situ UV absorption photometers, solar absorption photometers and ground based Lidar. A brief reference is made to the mm-waves method.

In the comparison of satellite and ground-based balloon and rocket ozone observations, there are two major elements of concern: the allowable space-time window between paired observations, and the intercalibration between ground-based stations when multiple stations are used. The precision statistics for the cross-validation of surface based and satellite total ozone measurements consists of three components: the precision of the two different measurement methods, plus the random differences due to ozone variability. If a sufficiently large sample of comparisons is obtained, the effects of random errors should approach zero, leaving only the systematic bias. It would be useful to know the systematic differences as a function of latitude, ozone amount, and season (and solar zenith angle if this is a relevant quantity). There is also a duality of need. The satellite experiments need a selected subset of well calibrated ground-based ozone data for validation of their observations, while the ground-based ozone network needs timely return flow of satellite data to flag possible anomalous data from a particular station.

## B. Total Ozone

The large natural variability of total ozone causes the greatest difficulty in detecting small trends related to anthropogenic activity. This variability includes long-period oscillations which are not well understood but must be removed if trends are to be detected. Therefore, the emphasis needs to be on precise, frequent, and long term measurements.

### 1. Dobson Spectrophotometer

Dobson ozone spectrophotometers presently serve as standard instruments for measurement of total ozone. However, the accuracy of the Dobson instrument is strongly dependent on the quality of its calibration and operation which can vary during an instrument's history. To attain the best performance a number of error sources must be considered and treated. These include (WMO Report No. 9); absolute instrument calibration at various points in a solar cycle, observational and instrumental errors, aerosol effects, ozone absorption coefficient uncertainties, interfering trace gas absorbing species, and uncertainties in the empirically derived relations between clear and cloudy zenith sky observations. The estimated ranges of various types of measurement errors for the Dobson spectrometer is given in WMO Ozone Report No. 11. In a detailed review of the Dobson spectrophotometer measurement accuracy, R. E. Basher (WMO Ozone Report No. 13) has indicated that instrument error sources set trend detectability limits of about 0.7 to 1.5 percent per year on the average, depending on the quality of the instrument set chosen to represent the global mean.

Before 1973, instrument calibrations were conducted independently at the various stations, if at all, which resulted in large errors (10-20%). Since 1974, increasing numbers of instruments

were modernized and calibrated by direct intercomparison with the recently designated World Primary Standard Dobson No. 83 (NOAA-Boulder). During 1981 seven standard lamps were circulated among seven groups of Dobson stations covering the globe. The first circuit was completed in 1983. A summary of these data is given in Table 1 which shows the percentage of 70 stations falling into relative errors ranging $< -2\%$ to $> 2\%$. The average correction to Dobson using the standard lamp is $-0.22\pm3.05$ percent.

Table 1

Percentage of Stations

| % difference | (< −2) | −2 to −1 | −1 to 0 | 0 to 1 | 1 to 2 | >2 |
|---|---|---|---|---|---|---|
| Standard Lamp | 19.4 | 16.1 | 22.6 | 19.1 | 8.1 | 14.5 |
| TOMS-Dobson (Bias removed) | 15.3 | 18.5 | 21.5 | 21.5 | 10.8 | 12.4 |

This indicates that about two thirds of the Dobson instruments making regular measurements are within ±2 percent interval. Table 1 also shows the discrepancy distribution of a 2-year comparison of overpasses of Nimbus-7 TOMS which can be considered a transfer standard. Similar results appear in both comparisons although the specific station distribution for the two comparisons are not the same. The reason for one-third of the comparisons being outside the 2% interval is not understood.

Uncertainty of the ozone absorption coefficients results in an estimated bias of 4-5 percent. This bias will vary by about ±2 percent for the maximum seasonal and latitudinal variations of ±15°C of the weighted mean temperature in the ozone layer. Preliminary recalculations of total ozone from selected Dobson stations using the latest ozone absorption coefficients indicates significant improvements in consistency of the estimated total ozone by different wavelength pairs.

The existing Dobson network (Umkehr and balloon stations as well) is very irregular, with a high density of stations in Europe, North America, and parts of Asia, low density over the tropics, and very few stations in the Southern Hemisphere. This uneven geographical distribution is a source of spatial sampling error when these data are used to determine global ozone content and trends. Weather conditions and operational factors that cause losses of data collection may result in additional biases since total ozone amounts are strongly correlated with the synoptic weather conditions. It has been shown from ground-based observations in Europe and from TOMS satellite data that the correlation between total ozone values decreases to nearly zero at a station separation distance greater than 1800 km (Bojkov, 1969). These results suggest that total ozone should be sampled with the resolution of mid-scale waves, or at intervals of 30° longitude or less, implying the need for about 100 well distributed total ozone stations globally to provide sufficient data to detect an ozone trend. Fewer well calibrated stations would be needed, however, to verify the satellite observations.

## 2. Other Instruments for Total Ozone

Approximately 20 stations of more than 40 using the M-83 broadband filter instrument routinely provide data to the World Ozone Data Center (WODC). Error studies (WMO Ozone Report No. 9) show that the average difference between the M-83 with the Dobson instrument is about 6 percent with errors in daily values of up to 30 percent. The errors are dependent on solar zenith angle, haziness and cloudiness. Recent comparisons of M-83 data with satellite data show better agreement but additional improvements (WMO Ozone Report No. 9) are still needed to make M-83 accuracy and precision of data comparable to that derived from the Dobson spectrophotometer. Great care is needed when using M-83 data for trend analysis.

The Canadian built Brewer-type grating spectrophotometer (Brewer, 1973) and the New Zealand Canterbury interference filter photometer use essentially the same UV technique as that of the Dobson instrument and are subject to similar error sources. The Brewer instrument operated in Toronto demonstrates accuracy comparable to a well calibrated Dobson instrument (differences with Dobson at direct sun observations are within ±1 percent) and long term data are expected to be useful in trend analyses. However, world wide utilization of Brewer is not foreseen before thorough field tests of the commercial instrument have been performed at several geographical locations and critically assessed. The New Zealand instrument in its few limited tests has failed to demonstrate long term stability.

## C. Vertical Ozone Distribution

A climatology of the vertical distribution of ozone is now being developed from satellite data. The verification of this data to a high degree of accuracy using ground-based, balloon, rocket, and possibly other satellite observations was the subject of this Workshop. The following discussion reviews the existing measurement capabilities.

### Umkehr Method

Umkehr observations are taken at about 20 stations mostly in the Northern Hemisphere. Only a few of them have taken observations quasi regularly for longer than 20 years. Research performed during the past decade indicates that with contemporary radiative transfer theory the Umkehr observations can be improved. After the new ozone absorption coefficients are formally accepted, development of the optimization inversion technique should be given a high priority and completed.

The Umkehr method makes use of measurements of zenith skylight by the Dobson spectrophotometer after dawn or before dusk over periods of about 3-5 hours for the conventional Umkehr method or 1-2 hours for the new, short Umkehr method. Derivation of ozone data from Umkehr observations employ an indirect inversion method and so suffers from inherent problems of limited vertical resolution and profile non-uniqueness. Because of this, random and systematic errors in any one particular observation will introduce errors in the inverted ozone profile. Factors that introduce random as well as systematic errors in the Umkehr profiles (WMO Ozone Report No. 9) include: instrument adjustments and calibration, nonrepresentativeness of first-guess ozone profiles, temperature dependence of the ozone absorption coefficients and aerosol optical effects. Nevertheless, it has been demonstrated that a large set of observations (e.g. monthly means) will substantially reduce the random error effects. Stratospheric aerosols have a major effect on the precision of the Umkehr measurements.

Studies of Dave et al. (1979) and DeLuisi, (1979) have shown that the stratospheric aerosol error results in a negative bias with a maximum value in layer 9 near 45 km decreasing nearly linearly to a negligible magnitude in layer 5 (centered ~ 26 km) with a positive bias below. The first-order variable controlling the error is the aerosol optical thickness. Higher order variables are distribution profiles of both aerosol and ozone, aerosol refractive index and phase functions. Fortunately, aerosol optical thickness can be measured (e.g. lidar) and for most applications, the higher order effects are negligible, e.g. sulfuric acid droplets which comprise the majority of stratospheric aerosol particles have extrememly small absorption in the ultraviolet. The short Umkehr method can improve the quality of the ozone observations. This method uses the A-C-D wavelength pairs, while the standard method uses the C-pair only. The usual observing time (3 to 5 hours) is reduced to only about 2 hours. This is expected to reduce the errors attributable to ozone variability. Another important advantage of the short Umkehr is that it requires measurements only to 89° solar zenith angle, rather than 90° for the conventional Umkehr reducing the error sensitivity to stratospheric aerosol by about 40 percent.

Table 2 illustrates the magnitude of stratospheric aerosol correction due to the Mt. Agung eruption that occurred in March 1963 (Reinsel et al., 1984). Corrections are considerably larger for very strong injections of aerosols into the stratosphere such as those from El Chichon. The precision to which stratospheric aerosol correction can be made is directly proportional to the error in the measurement of the stratospheric aerosol.

Table 2

Estimated Maximum Error to Umkehr Layers 9-5
Due to Mt. Agung Aerosols as Observed at Mauna Loa.

| Layer | Standard Umkehr | Short Umkehr |
|-------|-----------------|--------------|
| 9 | 12.8% | 7.7% |
| 8 | 8.2 | 4.9 |
| 7 | 5.2 | 3.1 |
| 6 | 1.8 | 1.1 |
| 5 | 0.8 | 0.5 |

Based on preliminary studies it appears possible that given a well managed Umkehr network, supplemented with accurate stratospheric aerosol information, and successfully accounting for sampling errors due to geography long-term (monthly and longer) means, could provide ozone data of sufficient precision to detect an ozone trend in the mid and upper stratosphere of about 2-4 percent/decade. Thus Umkehr measurements could also provide continuous data to compare with Tiros/SBUV/2 observations if experience shows that improved precision and intercalibrations have been achieved.

The present status of the Umkehr method are summarized in Table 3 with the comparison statistics compiled by Bhartia et al. (1984) where 43 matchups fo SBUV data with Boulder Umkehr observations were used. Ozone zalues are averaged over Umkehr layers and given in ozone column amounts (m-atm-cm).

Table 3

Station: Boulder (Umkehr)

| Layer No. | Umkher Layer Ozone | (‰σ) | SBUV Layer Ozone | (‰σ) | % Diff. | Std. Dev. of Diff, % | Correlation |
|---|---|---|---|---|---|---|---|
| 9 | 3.93 | (15.0) | 3.78 | (14.0) | −3.8 | 8.9 | .81 |
| 8 | 11.0 | (6.6) | 11.7 | (6.1) | 6.3 | 5.4 | .63 |
| 7 | 25.6 | (12.0) | 26.5 | (8.7) | 3.7 | 5.9 | .87 |
| 6 | 48.7 | (8.4) | 43.6 | (11.7) | −10.5 | 5.1 | .92 |
| 5 | 71.3 | (5.0) | 64.8 | (7.80) | −9.1 | 6.7 | 53 |

Balloon Ozonesondes

Balloon-borne ozonesondes provide in situ measurements of high vertical resolution to about 7-10 mbar with a precision of 5-20% depending on altitude. Various ozonesonde types have been used, but the most widespread are the wet chemical Brewer-Mast and ECC types. More than three-fourths of the available balloon-borne ozone soundings have been made in the Northern Hemisphere between 35° and 55° latitudes. In the tropics, a few soundings were conducted in the 1960s. Soundings were conducted from Natal, Brazil over the past 3 years (Kirchhoff et al. 1983) and the program will continue. Recently a series of balloon ozone soundings were conducted by the British Antarctic Survey in the Argentine Islands (65°S, 64°W) and provided a very valuable climatology in the Southern Hemisphere. Ozonesonde profiles are usually normalized to Dobson total ozone measurements and generally include corrections due to pump performance. After normalization of the integrated ozonesonde profiles to the Dobson measured total ozone, data from both types of sondes (Brewer-Mast and ECC) assume the Dobson instrument's systematic error. Height-dependent systematic measurement errors of about ±8% (WMO Report No. 9) occur for the sonde above about 25 mbar (26 km) due to uncertainties associated with the pump efficiency factors used in processing the data. However, pump efficiency factors can be measured to about 1-2%.

The accuracy of balloonsondes is dependent on the quality of the sonde's preflight preparation. $SO_2$ and $NO_2$ encountered in certain areas will also cause errors. A poorly prepared sonde may record only 50 percent of the real ozone amount. For this reason, correction factors outside the ranges of 0.8 to 1.4 for Brewer type sondes and 0.8 to 1.3 for the ECC type sondes are discarded. Additional errors result from inaccurate altitude determination from the ambient pressure measurement of pressures lower than 20 mbar if hypsometers are not used.

Evaluation of the performance of the ozonesondes flown during international comparison campaigns and studies of performance relative to well-run Umkehr stations indicate that the precision of the Brewer-Mast and ECC sondes is better than 5 percent in the 16-26 km layers, 20 percent in the troposphere, and about 12 percent up to 31 km (10 mbar). Further indications of performance above 10 mbar altitude of the ECC sonde are expected from results of the Balloon

Ozone Intercomparison Campaign conducted in 1983 and 1984 in Palestine, Texas.

Comparative statistics between 112 overpasses of SBUV over Hohenpeissenberg and comparisons between soundings at that station with Payerne (~ 330 km from Hohenpeissenberg) (Bhartia et al., 1984b) are shown in Table 4, where ozone values are averaged over Umkehr layers and given in ozone column amounts (m-atm-cm).

Table 4

Payerne/Hohenpeissenberg (Balloonsonde)

| Layer No. | Hohenpeissenberg Layer Ozone | (%σ) | Payerne Layer Ozone | (%σ) | % Diff. | Std. Dev. of Diff. | Correlation |
|---|---|---|---|---|---|---|---|
| 6 | 40.6 | (15) | 40.8 | (15) | 0.5 | 8.4 | 0.84 |
| 5 | 68.2 | (8) | 67.8 | (8) | −0.6 | 7.2 | 0.62 |
| 4 | 81.3 | (18) | 79.9 | (17) | −1.7 | 7.1 | 0.92 |
| 3 | 54.7 | (34) | 54.2 | (36) | −1.1 | 17 | 0.88 |
| 2 | 28.6 | (54) | 28.8 | (51) | 0.7 | 24 | 0.90 |

The data in Table 4 permits an estimate of the precision of the Brewer sondes since the standard deviation of the differences is a measure of the total random error in the two comparisons. Assuming each station has similar random error, the layer ozone amounts (or average pressure in the layer) from these two balloon sonde stations are measured with a precision of about 6 percent in layer 6 (28-33 km), 5 percent in layers 4 and 5 (19-28 km) and deteriorates to 12-15 percent near the tropopause. However, some of the observed differences in the lower layers could be due to ozone spatial variations between stations.

Rocket Ozonesonde

Rocket sondes provide data above balloonsondes and are imporant measurements in the validation of satellite data since they employ different techniques than SBUV or Umkehr. In the past some 600 rocket flights have been made utilizing four basic types of ozone measuring instruments. The WMO Rocket-borne Ozonesonde Performance Study (International Rocket Ozone Intercomparison) performed in October 1979 demonstrated large discrepancies among the different sondes. Precision estimates for the various sondes ranged from 3 to 30%.

The precision of rocket measurements depends on sampling rates, signal-to-noise ratios in telemetered data, sources of high frequency extraneous signals, radar height and vertical velocity precision, and on the required height resolution. The only currently used rocketsonde, an improved ROCOZ, is a solar UV absorption filter photometer where accuracy depends on wavelength calibration involving detector response, filter and other optical transmission characteristics, and ozone absorption coefficients. Ten ROCOZ launches have been carried out at Wallops Island, Virginia since August 1983. Included were two groups of four nearly simultaneous flights that demonstrated a repeatability in the measured ozone overburden of 4% at 55 km and 2% at 20 km. A preliminary estimate of absolute accuracy of 5-6% is based on measured solar irradiance at highest altitude. In addition the ROCOZ profile of cumulative ozone (55 km to 20 km) when added

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to the accompanying ECC sonde densities integrated from the ground to 20 km agreed with the Dobson results within ±3% for all ten flights. Evaluation of the performance of this system is continuing.

## Mass Spectrometer Beam System (MSBS)

The operation of the MSBS is based on gas expansion and formation of a molecular beam using a sequence of orifices and high speed liquid helium pumps (Mauersberger et al., 1981). The measurement can be optimized to accommodate the experiment for a particular altitude range during a balloon flight (e.g. 40-20 km). Before each flight the MSBS is calibrated in the laboratory using pure gases as well as gas mixtures at stratospheric pressures and temperatures. Calibrations for ozone are of particular importance. Recent studies have shown that an absolute accuracy of better than ±2% for a laboratory $^{38}Ar/O_3$ mixing ratio can be obtained. During the flight many mass ratios of stable, well-mixed atmospheric gases ($N_2$, $O_2$, Ar, Kr) are measured and compared with laboratory calibrations. Agreements to within ±1% have been found. Ozone mixing ratios are calculated using signals measured at mass 48, ($O_3$) and at 38 ($^{38}Ar$). Ozone mixing ratios with an absolute accuracy of about ±3% and a precision of 2 to 3% at 45 km and 1% at 30 km are claimed.

## In Situ Ultraviolet Absorption Photometers

UV absorption methods have the potential of providing in situ measurements of atmospheric ozone from the ground up to about 45 kilometers. In its simplest form the instrument consists of a mercury lamp, a sample chamber and a detector that measures the 254 nm radiation transmitted through the chamber. The ozone number density can be calculated from length of the cell, pressure, temperature, and the ozone cross section. This basic method has been implemented in a variety of ways (Hilsenrath and Ashenfelter, 1976, Mauersberger et al., 1981, Robbins, 1983, Proffitt and McLaughlin, 1983). Some of these instruments have flown 10 or more times.

Estimated absolute accuracy is about 3% at 25 km and 4% at 40 km. This includes a 2 percent uncertainty in the ozone absorption cross sections but not uncertainties due to wall losses. Losses in ozone due to collisions with the walls of the instrument remains controversial since some of the experimenters feel that such losses are negligible while others feel these losses could be as high as 30 percent at 40 kilometers (Ainsworth et al., 1981). Since wall loss is apparently not only pressure dependent but also instrument dependent, each experimenter has his own way of attacking the problem. The approaches include: laboratory calibration under flight conditions to verify that no wall loss occurs; in flight wall loss measurements; and in flight diagnostics with pumping speed changes to evaluate wall loss. Intercomparison of the measurements under flight conditions will help resolve this problem.

Both ground and inflight intercomparisons of the various balloon instruments and Umkehr have been made under the NASA Balloon Ozone Intercomparisons Campaign (BOIC) conducted in July, October 1983 and March 1984. The ground intercomparisons were made by comparisons with a National Bureau of Standards (NBS) standard absorption photometer at the NBS laboratories in Gaithersburg, Maryland and at the launch site in Palestine, Texas. Preliminary results from these flights are discussed after the next section.

## Differential Absorption Lidar

Ozone profiles have recently been extracted using a ground-based differential absorption LIDAR technique (DIAL)(Pelon and Megie, 1983). Briefly, a pair of laser beams of different wavelengths, $\lambda_1$, which is strongly absorbed by $O_3$, and $\lambda_2$, which is less strongly absorbed, are

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transmitted into the atmosphere colinear with the field of view of the receiver telescope. Transmitted photons at $\lambda_1$ and $\lambda_2$ are Rayleigh scattered back to the telescope interacting with $O_3$ along the round trip path. An $O_3$ profile is extracted from time gating the detector and the difference in absorption at $\lambda_1$ and $\lambda_2$. Because it is a differential technique many instrument factors cancel out, such as: the transmitted photon term, and the transmission efficiency of the detector train. Additionally the active nature of the technique allows, in principle, for measurements at any time of day, although daytime measurements have not yet been developed because of the complexity of the detector required to reject scattered solar flux.

At the present time both frequency doubled dye lasers and excimer lasers are being used as transmitters in $O_3$ DIAL instruments. Dye lasers offer broad tunability while the excimer lasers offer high peak and average powers. The frequency doubled dye laser system at the Observatory de Haute-Provence, France uses two pairs of frequencies with output energies on the order of 30-40 mJ to obtain an ozone profile from ground level to 40 km. The laser operates at 10 Hz and acquisition time is roughly 1 hour. The reported error below 25 km is approximately 5% with a vertical resolution of about 1 km. Above 25 km the range resolution decreases to 3 km and the error increases to $\sim$ 20% at the top of the altitude range.

Progress in high powered excimer lasers now make possible lidar measurements with much higher precision. Rothe et al. (1983) have used a XeCℓ excimer laser transmitting 150 mJ at 308 nm with a repetition rate of 50 Hz to measure $O_3$ profiles from 25-45 km. The reference wavelength is generated by Stimulated Raman Scattering in methane to 338 nm. This system returns a profile every 15 minutes up to 30 km with a reported precision of 1%. At 40 km the integration time increases to several hours for the same precision. In all cases vertical resolution is 1 km. Further improvements in signal-to-noise can be realized by increasing either the energy/pulse or repetition rate (or both) and by further opening the altitude resolution. A detailed treatment of possible systematic errors is still needed.

XeCℓ lasers with powers up to 100 watts are currently available which will further increase the sensitivity of the technique. Table 5 (McGee, private communication) offers the results of simulations of lidar sensitivity for a system employing a 100 W XeCℓ laser and a 60″ telescope operated at sea level with an integration time of one hour. The optical and electronic efficiency of the detector has been taken to be 5%.

Table 5 — $O_3$ Precision Simulations

| Altitude (km) | Altitude Resolution (km) | % Error | |
|---|---|---|---|
| | | Single Pulse | One Hour Integration |
| 25 | 0.5 | 2.9 (0) | 3.1 (−3) |
| 30 | 1.0 | 3.7 (0) | 4.0 (−3) |
| 42.5 | 2.5 | 2.8 (1) | 3.0 (−2) |
| 45 | 5.0 | 1.5 (1) | 1.6 (−2) |

The table points out some of the tradeoffs that can be made to increase the precision of various altitudes. Clearly the integration time can be significantly less than an hour at 25 km or the range cell can be decreased. Conversely at 45 km the range cell has been opened up to 5 km and an increase in integration time may be required.

Lidar techniques are beginning to mature out of the developmental stage and could be an important method for obtaining high quality ozone data in the mid to upper stratosphere with moderate to high temporal and spatial resolution. Preliminary results with operating systems and simulations using newer high power excimer lasers indicate that an independent verification of a trend on the order of 4% in ten years at 40 km is possible.

## D. Ozone Intercomparisons

Various ozone intercomparisons from balloon flights have been conducted over the past several years. Electrochemical sondes were intercompared in Hohenpeissenberg, 1978. Developmental and operational instruments were intercompared in Gap, France in 1981, the Balloon Intercomparison Campaign and Balloon Ozone Intercomparison Campaign, Palestine, Texas in 1983 and 1984, and MAP/Globus in France in 1984. The International Ozone Rocket Intercomparison conducted from Wallops Island, Virginia, in 1978 involved rocket experiments from Australia, Canada, Japan and the United States. Some of these results are reviewed here while others have been or will be published elsewhere. Data from the more recent flights are still being analyzed.

## Preliminary Results from the Balloon Ozone Intercomparison Campaign (BOIC)

The purpose of BOIC was to assess the accuracy and precision of various ozone measurement systems flown operationally and under development. The campaign involved investigators from Harvard University and the University of Minnesota, NOAA, and NASA Laboratories, Germany (Hohenpeissenberg) and Canada (AES). In situ UV photometers, chemical sondes, a mass spectrometer, and two solar UV absorption photometers were intercompared in the following three flight missions from Palestine, Texas: 1) a multiple instrument gondola carrying several in situ photometers, two solar UV absorption photometers and several chemical ozone sondes; (2) the University of Minnesota gondola carrying a mass spectrometer, NASA/JSC in situ photometer, a solar UV absorption photometer (ROCOZ) and NOAA ECC chemical ozone sondes; 3) a series of 16 small balloons, called Triplets, each carrying three each of the four chemical sondes from NOAA, NASA, Canada (ECC sondes) and Germany (Mast-Brewer sondes). Because of poor weather conditions and two balloon failures, these missions were not conducted simultaneously as originally planned. The Triplet flights were completed in July 1983 while the multiple instrument gondola was flown successfully in March 1984. The data are now being analyzed. Umkehr data from the Brewer and Dobson spectrophotometers and SBUV satellite ozone observations were also intercompared.

A comparison of calibration procedures and a laboratory intercomparison of instruments with the National Bureau of Standards (NBS) were also part of BOIC. Three in situ absorption photometers from NASA (GSFC and JSC), two from NOAA Aeronomy Laboratory and the four chemical ozone sondes were compared against the NBS absorption photometer which was used as an ozone reference standard.

Data from some of the tests and flights have been analyzed and the following is a summary of preliminary results. The standard deviation of the differences among 17 instruments against the NBS reference was about 11%. Some of the differences were systematic between instrument types. For example, the NASA ECC sonde compared about 10% high, the NOAA ECC compared about 4% high and the Mast-Brewer about 10% low against the NBS reference. The UV in situ photometers read within about ±5% of the NBS reference. These differences (particularly among the chemical sondes) appeared in flight at the lower levels, however, changed at higher altitudes

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indicating height dependent errors.

The average ozone profiles taken in the Triplet flights over the 18 day period are compared in Figures 12a and 12b which illustrate the average departure of each sonde type from a mean profile (from all soundings) before and after each profile was normalized to total ozone. Before and after normalization differences between the Mast-Brewer and ECC type sondes are large in the troposphere. This is consistent with the results of Hohenpeissenberg 1978 intercomparison. Before normalization the Mast-Brewer sonde data are systematically lower than ECC data with an absolute bias at all levels. After normalization that data become higher than the others near the ozone maximum. This results from the percentage correction (normalization) to data that are biased. The standard deviation of the 18 day set for each sonde type ranged from 5-10% where the AES data was the highest. One can conclude from BOIC that after normalization the sondes most likely agree with each other to within about 10% except in the troposphere.
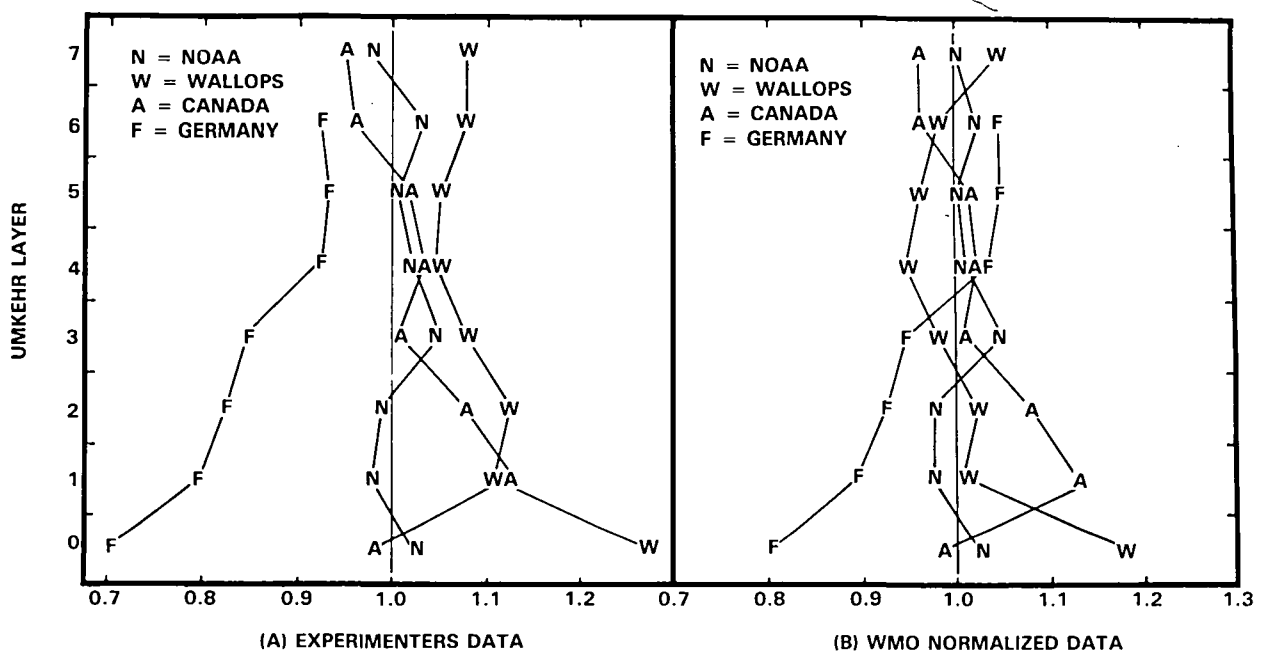


Figure 12. BOIC Triplet flights, ratio of instrument average with average of all instruments during Triplet flight period. (a) Experimenters data, (b) WMO normalized data.

Intercomparison of sondes from the same group (3 sondes together by NOAA/GMCC and by NASA/GSFC) showed excellent agreement after pressure measurement errors were removed. Differences were of the order of 5% in the troposphere and stratosphere even before normalization. This implies that given an established procedure the electrochemical sondes can give high precision. However, when comparing these two systems with each other, biases exist which may be explained by differences in solution concentration and/or pump efficiency corrections.

During the BOIC measurement period SBUV satellite data were extracted over Palestine, Texas and compared with balloonsonde and Umkehr averages for that period. The data consisted of 7 Umkehr, 12 satellite and about 40 balloon soundings. In general the measurements agree to within their standard derivations ($\sim$ 10% in the stratosphere) except in layer 7 (centered near 6 mbar) where the balloon sondes appear to be 20% lower.

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Data were taken from 5 UV photometers on ascent and descent on the multiple instrument gondola which reached an altitude of about 42 km (2.2 mbar). During ascent there were differences of 5-10%. As the ascent rate decreased and the balloon reached float altitude the differences grew to larger than 20%. It should be noted that ozone concentrations and pressures are very low at these levels and gondola contamination may be significant. On descent, at pressures higher than 5 mbar, the measurements agreed significantly better with each other. The agreement was about 3%. This improved agreement occurred even though the descent rate was about 1/2 the ascent rate. ECC sondes from NOAA, AES and NASA were also compared with the UV photometers. In the troposphere variability of the sondes was 20% and more. In the stratosphere (50 to 10 mbar) the NOAA sondes agree to better than 5% among themselves and with the UV photometers. At pressures lower than 10 mb the ECC sondes fall off rapidly relative to the UV photometers. If the UV photometers are considered to be correct, this fall off is consistent with the comparison of balloons, Umkehr and satellite data.

There is evidence that contamination from the balloon and/or platform can affect the quality of the ozone measurements. Laboratory comparisons simulating stratospheric conditions are being planned as a follow on to BOIC. Comparisons on a smaller scale than BOIC should be continued.

Other Ozone Intercomparisons

Intercomparisons were performed among several ground based and balloon ozone instruments in Gap, France in June 1981. The intercomparison campaign is described in detail in a special issue of *Planetary and Space Science* (Volume 31, No. 7, 707-811, 1983). Some of these results are summarized below. From 0-25 km there was an average of 10% difference between Mast-Brewer and the ECC chemical ozone sondes and the NASA/JSC in situ UV photometer (the latter two agreeing well). For the electrochemical sondes differences reached a factor of 2 above 25 km. Comparisons between Lidar and Umkehr were on the order of ±15% up to 25 km. Comparisons were made between chemiluminescent and UV in situ instruments and two Solar UV absorption photometers as well as electrochemical sondes between 20 and 35 km. There were 10-15% differences between the in situ photometers; however, there was a 20% systematic difference between them and the solar absorption instruments over the entire altitude range. Since the solar absorption instruments agreed to better than 10%, this result implies systematic differences between in situ and remote ozone sensors. Results from the BIC and BOIC flights will be very important in verifying this result.

In the 1978 Hohenpeissenberg intercomparison, tests were performed between two types of Brewer sondes (from FRG and GDR), the NASA ECC, and the Japanese KC-68 sondes. In the troposphere the ECC was about 12% higher than the mean values. Near 15 mbar the KC-68 sonde was about 7% lower than the mean. Between these two levels there seemed to be no height dependent differences for any of the instruments. There was a ±4% random difference among the sonde types at these levels.

E.    Shuttle SBUV

As discussed earlier in this report, the stability of the SBUV/2 satellite instrument must be accurately known in order to derive interannual and long term trends in ozone. The in-flight diffuser plate reflectance check will provide some data on instrument stability. Space Shuttle

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flights carrying an SBUV/2 instrument, however, will provide an opportunity to conduct regular and direct calibration checks of the SBUV/2 satellite measurements by comparing nearly coincident observations taken by the two instruments.

A Shuttle SBUV (SSBUV) in orbit calibration check can be achieved by comparing the measured solar irradiance and the backscattered radiances in the ozone absorption channels when both instruments are viewing the same Earth scene. Periodic flights (about two per year) of the SSBUV are adequate to achieve the required precision of 1% or better prior to and after each flight. In addition its calibration will be monitored during flight.

The nonlinear relationship between the ozone latitudinal distribution with height and the measured radiances was discussed in Chapter 2 (Figure 4). In this example a 5% uniform (in wavelength) radiance error is assumed. The corresponding ozone error at 3 mb (40 km) ranges from 4 to 9% depending on latitude. Consequently ground truth performed at one location has only marginal value in determining instrument calibration at other locations. The problem is even more complicated when the radiance errors are wavelength dependent which is more likely to occur. The SSBUV, however, will provide an instrument calibration independent of an algorithm and therefore independent of latitude.

An in-orbit calibration check is defined as the ability to detect a bias or systematic differences between the observations from the satellite instrument and the freshly calibrated Shuttle instrument. This bias can be detected once random errors in the observations are removed by repetitive comparisons. The accuracy to which the bias can be detected depends on the precision of the observations (from both instruments), ozone variability and the number of comparisons. The estimates of precision for the comparisons are at the $2\sigma$ (95% confidence) level.

Figure 13 illustrates predicted ozone trends derived from one-dimensional photochemical models as function of altitude for several cases. The solid curve depicts the predicted change from 1970 to the present time from combined anthropogenic sources (CFC, $CO_2$, $N_2O$, $NO_x$). The dashed curve depicts this prediction extended to 1990 using best estimates of anthropogenic releases (Wuebbles et al., *JGR, 88*, 1983). The striped area is an estimate of the change in ozone over a solar cycle due to solar variations (S. Chandra, private communication, 1983). The range of ozone change is a result of varying the change of the solar ultraviolet spectral irradiance possible over a solar cycle.
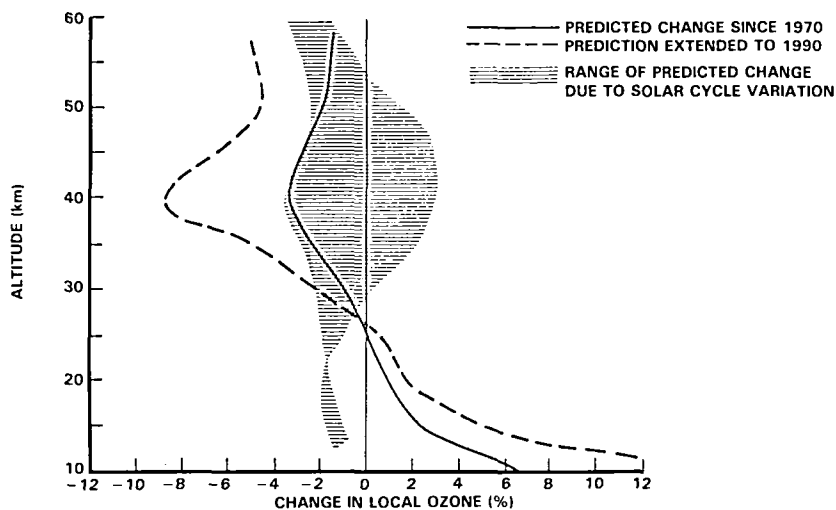


Figure 13.  Predicted trends in ozone due to anthropogenic causes and solar cycle variations.

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The details of these predictions may vary slightly with new input data, computational procedures, etc.; however, it is quite clear that changes will be small and if detected may not be easily explained. For one scenario of solar cycle variation, the ozone change nearly mimics a change predicted from anthropogenic causes, while for another, the change is in the opposite direction at 40 km.

Backscattered radiance (or albedo) trends at the BUV wavelengths which would result from the predicted ozone trends due to CFC releases have been calculated by Frederick and are illustrated in Figure 14 (private communication). The trend is reported as the ratio of the radiance for a given year to the unperturbed value in 1970, at the BUV wavelength. The trends for the period 1984 to 1992 are summarized in Table 6.

Table 6 — Radiance Trends

| BUV Wavelength (nm) | Altitude (km) | % Radiance Change 1984 - 1992 | % Per Year |
|---|---|---|---|
| 255.5 | 51 | 0.6 | .08 |
| 273.5 | 50 | 0.9 | .11 |
| 283.0 | 48 | 2.0 | .25 |
| 287.0 | 44 | 2.2 | .28 |
| 292.2 | 40 | 2.51 | .31 |

The minimum requirement for in-orbit calibration should therefore be the ability to detect an instrument drift at least as small as the trends in Table 1 at the shortest wavelength, i.e., 0.08% per year at the 95% confidence level.



Figure 14. Approximate radiance trends at SBUV wavelengths corresponding to ozone changes, predicted by photochemical models assuming a trend at 40 km of $-0.5\%\ yr^{-1}$.

For a given Shuttle SBUV mission the accuracy to which a bias (calibration drift) can be detected is statistically determined from the number of and the precision of the measurements and the ozone field variability. The statistical procedure for detecting an instrument drift smaller than the ozone trend can be derived from the analyses in Appendices A and B of thi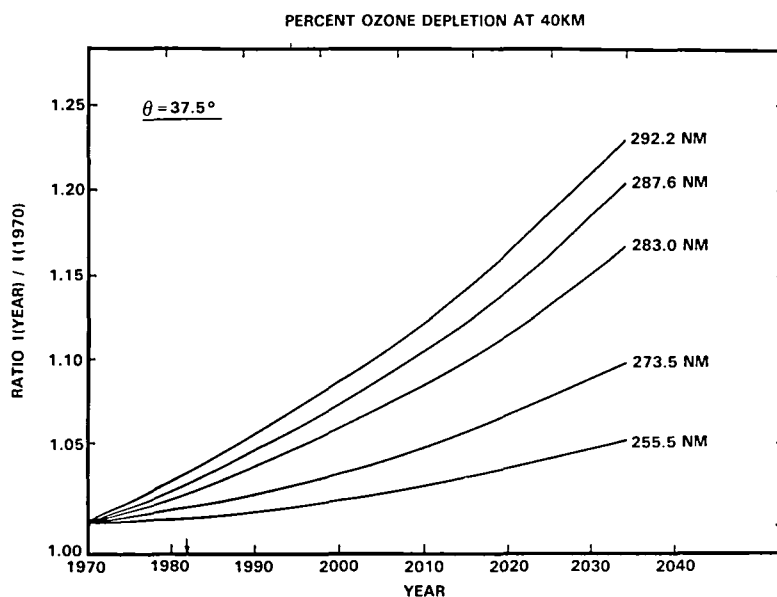s report. The precision of the SBUV measurements and the variability for a given comparison (from space) is 1% and lower. There can be as many as 45 comparisons (matchups within 1 hour) for a given 3-day Shuttle SBUV mission. These are more than adequate to detect a bias (calibration drift) between the satellite and Shuttle SBUV instruments at one point in time.

Using the statistical analyses appearing in Appendix B one can derive the number of Shuttle missions per year needed for a given observation period (5, 10, 15, etc., years) to detect a drift in the satellite system smaller than the expected trend. The variables in this derivation are the ozone variability, comparisons per mission, missions per year, and the observing period. The longer the observing period the fewer missions per year are required. Trends (or drifts) will be detected sooner at 40 km than at 50 km for example. A reasonable scenario using arguments developed in Appendix B is one to two Shuttle SBUV missions per year for about 10 years.

The above discussion deals only with calibration of SBUV channels which are used for deriving ozone profiles. Radiances used to derive total ozone are highly variable since they originate at the Earth's surface (clouds, oceans, land, etc.). Therefore in-orbit comparison of these radiances would be unacceptably inaccurate and the only reasonable calibration check would be through the total ozone algorithm which accounts for surface reflectivity. The procedure for this has been developed and the calculations demonstrate that a 1% calibration (95% confidence level) in the satellite inferred total ozone can be accomplished with a 3-day Shuttle mission.

In order to detect solar irradiance variaations, the calibration and statistical computational procedures are similar to those developed for ozone; however, the observing requirements differ. In Figure 1 it was shown that solar variations will cause ozone changes comparable to those caused by anthropogenic sources. Clearly then, long term measurements of the solar spectral irradiance must be precise enough to detect these variations. The solar irradiance measurements from BUVs on Nimbus-4, AE-E, and Nimbus-7 degraded considerably more than the natural variability expected in the solar ultraviolet irradiance.

The need to monitor solar irradiance variations in the ultraviolet over a solar cycle were discussed in Chapter 1. These variations (Lean, 1983) are included in the ozone trend calculations illustrated in Figure 13 and are listed in Table 7.

Table 7 — Solar Irradiance

| Wavelength (nm) | Solar Cycle Ratio (max/min) | % Per Year |
|---|---|---|
| 180 - 210 | 1.20 | 4.0 |
| 210 - 260 | 1.10 | 2.0 |
| 260 - 300 | ~1.01 | ~0.2 |

At the shorter wavelengths the expected solar variation are significantly larger than the minimum required for detecting instrument drifts for ozone profile (albedo) measurements. Therefore ultraviolet variations due to solar cycle effects can be detected with the SSBUV and the satellite observations. The Tiros-N SBUV/2 has no on-board check of the solar irradiance calibration and it is this measurement that is most sensitive to the effect of post-launch degradation.

In this analysis, the long term precision of the absolute radiometric standards are not included. The maintenance of these standards is a developing technology and therefore the establishment of an ultraviolet calibration facility and standards is of crucial importance to a successful long term ozone measurement program. The precision of the standards is expected to be of the order of 1% and could be included in the computations for a more rigorous analysis. Nevertheless, the computations performed here are reasonable estimates of the SSBUV capability relative to alternative verification systems, since the alternatives also ultimately rely on the long term stability of the absolute standards.

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APPENDIX A

Method for Determining the Number of Correlative Measurements
Required to Validate the SBUV/2 Ozone Retrievals

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The assumptions and procedure in the calculation are as follows.

1. The correlative measurements system has a precision of $\pm\epsilon_{MS}$. The standard deviation of an infinite number of measurements would be $\sigma_{MS} = \epsilon_{MS}X$, where X is the mean ozone amount, and all errors are random. In addition, the SBUV/2 system has a precision of $\sigma_{SBUV} = \epsilon_{SBUV}X$.

2. If we performed an infinite number of ozone measurements in coincidence with SBUV overpasses and considered the difference between each pair, correlative result minus SBUV result $X_{cm} - X_{SBUV}$, these values would form a normal distribution whose mean is zero or a value equal to the systematic bias between techniques. The standard deviation of these differences is:

$$\sigma^2 = \sigma^2_{O_3} + \sigma^2_{MS} + \sigma^2_{SBUV} = (\epsilon^2_{O_3} + \epsilon^2_{MS} + \epsilon^2_{SBUV}) X^2 \tag{1}$$

3. The term $\sigma_{O_3} = \epsilon_{O_3}X$ accounts for the fact that the ozone profile sensed by an in situ technique is not identical in terms of spatial smearing to that from the satellite instrument. In addition the two measurements are never exactly coincident in space and time and, thus, do not observe precisely the same ozone field. We take the error so-incurred to be random.

4. If there are "n" near coincident measurements, the standard error of the computed mean is $\sigma/\sqrt{n}$. There is a 95% probability that the *true* difference (as would be obtained from an infinite number of measurements) lies within $\pm1.96\,\sigma\sqrt{n}$ of the *computed mean difference. If* $\delta$ is the tolerable uncertainty in this computed result, expressed as a fraction of the ozone amount, X, then:

$$\delta = \frac{1.96}{\sqrt{n}} \frac{\sigma}{X} \tag{2}$$

or

$$n = (\frac{1.96}{\delta})^2 (\epsilon^2_{O_3} + \epsilon^2_{MS} + \epsilon^2_{SBUV}) \tag{3}$$

Equation 3 defines the number of correlative measurements required for specified error tolerances in the mean ozone ($\delta$), measurement system precision ($\epsilon_{MS}$), atmospheric ozone scene variability ($\epsilon_{O_3}$). and SBUV/2 precision ($\epsilon_{SBUV}$).

5. The approach taken above assumes that all errors are random. In actual practice this is never the case. For example, comparisons of Umkehr measurements with near coincident SBUV overpasses show a systematic bias which varies with season. Furthermore, in this case the n measurements cannot be treated as totally independent pieces of information. A detailed evaluation of these complicating effects can only be made after examining a large amount of data obtained by a given correlative measurement technique. For this reason, in estimating the

number of measurements needed from equation 3, one is advised to choose somewhat larger values of the random errors than would be estimated from a strict adherence to their definitions. This procedure accounts, at least in part, for errors incurred in the simplified statistical development.

6. The degree of ozone variability can be defined from Nimbus-7 SBUV measurements. For a latitude band of width 10 degrees centered on 38-39 degrees North and a pressure layer extending from 1.95 - 3.90 mb, the ratio of the standard deviation the zonal mean varies from 0.022 (June) to 0.123 (December) with an annual average of 0.059. Values computed for a 10 degree latitude by 20 degree longitude block are essentially the same as the results which include all longitudes. For the periods of spring, summer and autumn values of $\epsilon_{O_3}$ in the range 0.02 to 0.05 are reasonable. The SBUV/2 precision is $\epsilon_{SBUV} = 0.03$ in all cases reported below. This value is consistent with that reported in the text for a pressure of 3 mb.

Table 1 presents the number of coincident measurements required to attain a 95% confidence of replicating retrieved SBUV/2 ozone values between 1.95 and 3.90 mb to a precision $\delta$ in the range 0.01 to 0.05. Reasonable choices are $(\delta, \epsilon_{O_3}, \epsilon_{MS}) = (0.01, 0.02, 0.03)$ and $(0.01, 0.05, 0.03)$, implying 69 to 165 measurements. If the measurements were performed as close in time as possible, but still coincident with SBUV overpasses, the error involved in neglecting seasonally varying biases between the measurement systems would be minimized.

Table 1. NUMBER OF OZONE MEASUREMENTS COINCIDENT WITH SBUV OVERPASSES
NEEDED TO ACHIEVE VARIOUS PRECISIONS

A. $\delta = 0.01$  Specify bias to within 1% of the ozone amount near 3 mb.

| $\epsilon_{O_3}$ | $\epsilon_{MS}$ | | |
|---|---|---|---|
| | 0.03 | 0.05 | 0.10 |
| 0.00 | 69 | 131 | 419 |
| 0.02 | 85 | 146 | 434 |
| 0.05 | 165 | 227 | 515 |
| 0.10 | 453 | 515 | 803 |

B. $\delta = 0.02$  Specify total bias to within 2% of the ozone amount near 3 mb.

| $\epsilon_{O_3}$ | $\epsilon_{MS}$ | | |
|---|---|---|---|
| | 0.03 | 0.05 | 0.10 |
| 0.00 | 17 | 33 | 105 |
| 0.02 | 21 | 36 | 109 |
| 0.05 | 41 | 57 | 129 |
| 0.10 | 113 | 129 | 201 |

C. $\delta = 0.05$  Specify total bias to witin 5% of the ozone amount near 3 mb.

| $\epsilon_{O_3}$ | $\epsilon_{MS}$ | | |
|---|---|---|---|
| | 0.03 | 0.05 | 0.10 |
| 0.00 | 3 | 5 | 17 |
| 0.02 | 3 | 6 | 17 |
| 0.05 | 7 | 9 | 21 |
| 0.10 | 18 | 21 | 32 |

APPENDIX B

Measurement Requirements for the Detection
of Ozone Trends

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# Statistical Development

The objective of this Appendix is to address the following question. If we wish to detect a trend in the vertical distribution of ozone to a high confidence level at a specific location (e.g., a lidar site, rocket or balloon launch facility), how many measurements are required and over what time period would the data collection have to extend? Specific issues that are considered here include the impact of (1) short term ozone variability over the measurement site and (2) the precision of the measuring instrument on our ability to detect trends to a given confidence limit.

Consider a time series of ozone measurements $X_i$, i = 1, 2, 3, . . . , n from which all periodic components (annual, semiannual, quasi-biennial) have been removed. A regression model including a linear trend is given by:

$$X = b_0 + b_1 t + \epsilon \tag{1}$$

where the true trend in units of ozone abundance per year is $b_1$ and $\epsilon$ represents a deviation about the trend line. We assume a correlation to exist between $\epsilon$ values determined for two adjacent measurements separated by a time interval $\Delta t$. This is described by $\phi = e^{-\lambda \Delta t}$ and expresses the fact that n separate measurements provide fewer than n independent pieces of information on atmospheric ozone. Separate measurements become uncorrelated only when the time between them becomes long compared to $1/\lambda$. The least squares estimator of the trend is $b_1$ given by:

$$b_1 = \frac{\sum\limits_{i=1}^{m} [(X_i - \bar{X})(t_i - \bar{t})]}{\sum\limits_{i=1}^{n} [(t_i - \bar{t})^2]} \tag{2}$$

where an overbar denotes the mean of n points. The variance of the estimated trend, $\sigma^2(\hat{b}_1)$. with the assumption that the function $\phi$ describes the autocorrelation of errors is:

$$\sigma^2(\hat{b}_1) = \frac{(1 - \phi^2)}{(1 - \phi)^2} \frac{\sigma^2(X)}{\sum\limits_{i=1}^{n} [(t_i - t)^2]} \tag{3}$$

where $\sigma(X)$ is the variance of the ozone measurements (Whittle, 1963; Neter and Wasserman, 1974). Let the flights be spaced at equal time intervals, $\Delta t$, so that $t_i = t_1 + (i - 1)\Delta t$. With this relationship the summation in the denominator of equation 3 is:

$$\sum\limits_{i=1}^{n} [(t_i - \bar{t})^2] = (\Delta t)^2 n(n+1) [\frac{2n+1}{6} - \frac{n+1}{4}] \tag{4}$$

The combination of equations 3 and 4 with the assumption that n $\gg$ 1 yields:

$$\sigma^2(\hat{b}_1) = 12 \, \frac{(1-\phi^2)}{(1-\phi)^2} \, \frac{\sigma^2(X)}{\Delta t^2} \, \frac{1}{n^3} \qquad (5)$$

There is a 95% confidence level that the true trend lies within a range $\pm 1.96 \, \sigma(\hat{b}_1)$ about the computed value $\hat{b}_1$. If the 95% confidence limit, $\delta$, is expressed as a fraction of the true mean ozone amount, $\mu$, then:

$$\delta = 1.96 \, \frac{\sigma(\hat{b}_1)}{\mu} \qquad (6)$$

or, using equation 5,

$$\delta = \frac{1.96\sqrt{12}}{\Delta t} \, \frac{\sigma(X)}{\mu} \, [\frac{1-\phi^2}{(1-\phi)^2}]^{1/2} \, n^{-3/2} \qquad (7)$$

The number of measurements, n, required to predict a trend to a 95% confidence limit $\delta$ is then:

$$n = 3.59 \left\{ [\frac{\sigma(X)}{\mu}]^2 \, \frac{1}{\Delta t^2 \delta^2} \, [\frac{1-\phi^2}{(1-\phi)^2}] \right\}^{1/3} \qquad (8)$$

For numerical evaluation we assume the fractional variance of the ozone measurements to consist of (1) a random short term variability, $\epsilon_{STV}$, as would be associated with movement of an inhomogeneous ozone field over the measurement site, and (2) a random error in the observing instrument itself, $\epsilon_{INST}$. We then have

$$[\frac{\sigma(X)}{\mu}]^2 = \epsilon^2_{STV} + \epsilon^2_{INST} \qquad (9)$$

A potentially significant component, interannual variability, is not explicitly treated in the formulation. This cannot be included in the sense of a random error since, for example, a correlation exists between all measurements collected in a period of anomalously low ozone. Consideration of such complications is beyond the scope of this derivation.

For numerical evaluation of equation 8 we must choose (1) the fractional error tolerable in in the trend determination, $\delta$, (2) the time interval between two consecutive ozone measurements, $\Delta t$, and (3) the time scale, $\lambda$, of the autocorrelation function $\phi = e^{-\lambda \Delta t}$. Also required are (4) the random error arising from short term ozone variability over the measurement site, $\epsilon_{STV}$, and (5) the precision of the measuring instrument, $\epsilon_{INST}$.

Equation 8 contains several pieces of information that must enter the strategy formulation stage of a correlative measurements program. First, since the autocorrelation function, $\phi$, always decreases with increasing $\Delta t$ one can show that the total number of measurements, n, must decrease with increasing $\Delta t$, the time period between consecutive measurements. It is therefore not true that simply performing a greater number of measurements leads to an improved trend determination.

In fact, the tables show that the number of measurements decreases dramatically as the time period between consecutive data points increases from two days to one year. However, a trade-off must be made between the total number of measurements and the total duration of the program, $D = (n - 1)\Delta t$. This duration increases with the spacing between measurements even though n alone decreases with $\Delta t$.

Another major consideration in the numerical results is the autocorrelation function $\phi = e^{-\lambda \Delta t}$. So long as $\Delta t \leq 1/\lambda$ the total duration of the measurement effort, D, is insensitive to $\Delta t$ even though the total number of measurements, n, increases greatly with $\Delta t$. This shows that if adjacent measurements are very highly correlated, then increasing the number of data points does not significantly increase the information available for trend detection. As an example consider the case in Table 3-2 with $\epsilon_{INST} = 5\%$, $\delta = 0.2\%$ year$^{-1}$, and $\lambda = 3.33 \times 10^{-2}$/day. If one performed a measurement every two days, then a total of 3625 data points over a period of 19.9 years would be needed for an acceptable uncertainty in trend detection. If the spacing between measurements is increased to 28 days, the required total duration of the effort is nearly unchanged, being 20.3 years, although the total number of measurements has shrunk to only 265. Hence, when the autocorrelation function approaches unity, the factor of 3525/265 = 13.7 increase in measurements is of essentially no value for improving one's confidence in trend detection. Clearly, a firm strategy for trend detection must include a realistic determination of the autocorrelation function from the available ozone data base.

## Numerical Evaluation

The Nimbus-7 SBUV ozone data base provides the information required to evaluate the short term, presumed random, ozone variability over a given location. For the mid-latitude and tropical analyses we selected areas 10 degrees in latitude by 20 degrees in longitude centered on 38 degrees north and the equator respectively. For each month, m, in the period November 1978 through October 1979 we evaluated both the mean ozone amount, $X_m$, in the pressure layer 1.95–390 mb where the predicted trend in ozone arising from CFC-related chemistry is a maximum, and the standard deviation $\sigma_m$. We then take $\epsilon_{STV}^2$ to be the mean square value defined by:

$$\epsilon_{STV}^2 = \frac{1}{12} \sum_{m=1}^{12} (\frac{\sigma_m}{X_m})^2 \tag{10}$$

The resulting values are $\epsilon_{STV} = 4.02 \times 10^{-2}$ for mid-latitudes and $\epsilon_{STV} = 2.10 \times 10^{-2}$ in the tropics.

The range of $\delta$ values adopted here is based on the predicted magnitude of the CFC-induced ozone trend near 40 km. For detection of a trend to be definitive, the 95% confidence limit on the results should be less than the trend itself. We therefore consider three values of the confidence limits, being $\delta = 0.1\%$/year, 0.2%/year, and 0.4%/year. The value $\delta = 0.2\%$/year is a reasonable one to adopt in developing a measurement strategy. Finally, we select a range of random errors for the measuring instrument between 0 and 20%. A value of 5% is reasonable for strategy formulation.

The selection of numerical values for the autocorrelation function is the most uncertain portion of the evaluation. With the form $\phi = e^{-\lambda \Delta t}$ we examine the cases $\lambda = \infty$, $8.00 \times 10^{-1}$/day, and

$3.33 \times 10^{-2}$/day. The first value corresponds to the limiting case where consecutive measurements are completely independent regardless of how closely spaced in time they occur. The second value is based on analyses of TOMS total ozone (A. J. Miller, private communication, 1984). We regard this is a physically realistic case. Finally, the value $\lambda = 3.33 \times 10^{-2}$/day corresponds to an e-folding time of 30 days and implies that measurements made on consecutive days are highly dependent, $\phi(\Delta t = 1 \text{ day}) = 0.97$. For strategy formulation the value $\lambda = 8.00 \times 10^{-1}$/day should be adequate, although a study of the available ozone profile data should be performed to better define the autocorrelation function.

Finally, the numerical values of $\epsilon_{STV}$ and $\delta$ adopted here are suited to atmospheric behavior near the 40 km level. Extension of the analysis to other altitudes would simply require evaluation of equation 8 using a new set of parameters. However, predicted $\delta$ values at levels other than near 40 km are small compared to the 0.1-0.4%/year range adopted above. A correspondingly greater number of measurements would then be required for trend detection. However, inspection of Tables 1-6 shows that even with $\delta$ values appropriate to the 40 km region, a measurements program designed to detect the expected ozone trends requires a sizeable resource allocation. We therefore choose to restrict consideration of the altitudes where the trend is predicted to be a maximum.

# Use of the Tables

The set of Tables 1 through 6 is ordered according to (1) mid-latitude or the tropics and (2) the parameter $\lambda$ of the autocorrelation function. Each major table is further divided into three sub-tables, one for each $\lambda$ value, 0.1, 0.2, and 0.4%/year. Each sub-table is structured according to the random error of the measuring instrument, $\epsilon_{INST}$, and the time interval between consecutive measurements, $\Delta t$. Two table entries in the form n/D correspond to each $\epsilon_{INST}$, $\Delta t$ pair where n is the total number of measurements required and D is the duration of the program in years. For example, in Table 2-2 with $\lambda = 8.00 \times 10^{-1}$/day, detection of an ozone trend near 40 km to a 95% confidence limit of ±0.2%/year using an instrument containing a random error of 5% with measurements made at 14-day intervals, requires a total of 319 data points over a 12.2 year period.

# Recommendations

It is clear from Tables 1 through 6 that the number of measurements and the duration of the trend detection effort vary tremendously depending on the parameters adopted in the calculation. We here take $\delta = 0.2$%/year as the largest acceptable confidence limit on the computed trend and assume the precision of the measuring instrument to be ±5%. Furthermore, we also assume that trend detection should be accomplished in the desired tolerance in less than 15 years. With the adopted autocorrelation $\delta = 8.00 \times 10^{-1}$/day, the acceptable alternatives from Tables 2-2 and 5-2 are as follows:

1. Mid-latitudes ($\delta = 0.2$%/year)
   a. 1336 measurements over 7.3 years conducted at 2 day intervals
   b. 319 measurements over 12.2 years conducted at 14 day intervals

A third alternative that very nearly meets the criteria, taking 15.4 years for trend detection to the ±0.2% level is:
   c. 201 measurements over 15.4 years conducted at 28 day intervals

2. Mid-latitudes ($\delta = 0.1$%/year)
   a. 2121 measurements over 11.6 years conducted at 2 day intervals.

For tropical latitudes the smaller atmospheric variability allows a larger number of alternatives within the 15 year time frame. These are:

3. Tropics ($\delta = 0.2$%/year)
   a. 1195 measurements over 6.5 years conducted at 2 day intervals
   b. 285 measurements over 10.9 years conducted at 14 day intervals
   c. 180 measurements over 13.7 years conducted at 28 day intervals

4. Tropics ($\delta = 0.1$%/year)
   a. 1897 measurements over 10.4 years conducted at 2 day intervals

Subject to the requirements $\delta < 0.2$%/year, $\epsilon_{INST} = 5$%, and $\lambda = 0.80$/day, the recommended number of measurements required for ozone trend detection at 40 km in less than 15 years is the smallest of those given above. For mid-latitudes this is 319 measurements made over 12.2 years and for the tropics 180 measurements over 13.7 years.

Table 1. Mid-latitude Site ($\epsilon_{STV} = 4.02 \times 10^{-2}$)

1-1    $\delta = 1.0 \times 10^{-3}$/year     ($\pm 0.1\%$/year)
      $\lambda = \infty$

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 1356/7.4* | 370/14.2 | 233/17.8 | 106/26.3 | 42/41.1 |
| 3 | 1571/8.6 | 429/16.4 | 271/20.7 | 123/30.5 | 49/47.8 |
| 5 | 1851/10.1 | 506/19.4 | 319/24.4 | 145/36.0 | 57/56.5 |
| 10 | 2616/14.3 | 715/27.4 | 450/34.5 | 205/50.9 | 81/80.3 |
| 20 | 4003/21.9 | 1094/41.9 | 689/52.8 | 314/78.1 | 124/123.4 |

1-2    $\delta = 2.0 \times 10^{-3}$/yr     ($\pm 0.2\%$/year)
      $\lambda = \infty$

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 854/4.7 | 233/8.9 | 147/11.2 | 67/16.5 | 27/25.5 |
| 3 | 990/5.4 | 271/10.3 | 170/13.0 | 78/19.1 | 31/29.8 |
| 5 | 1166/6.4 | 319/12.2 | 201/15.3 | 92/22.6 | 36/35.2 |
| 10 | 1645/9.0 | 450/17.2 | 284/21.7 | 129/32.0 | 51/50.2 |
| 20 | 2522/13.8 | 689/26.4 | 434/33.2 | 198/49.1 | 78/77.4 |

Table 1 (con't)

1-3  $\delta = 4.0 \times 10^{-3}/\text{yr}$ $\qquad$ $(\pm 0.4\%/\text{year})$

$\quad \lambda = \infty$

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 538/2.9 | 147/5.6 | 93/7.0 | 42/10.3 | 17/15.7 |
| 3 | 624/3.4 | 170/6.5 | 107/8.2 | 49/11.9 | 19/18.4 |
| 5 | 735/4.0 | 201/7.7 | 127/9.6 | 58/14.1 | 23/21.8 |
| 10 | 1038/5.7 | 284/10.8 | 179/13.6 | 82/20.1 | 32/31.3 |
| 20 | 1589/8.7 | 434/16.6 | 174/20.9 | 125/30.8 | 49/48.4 |

*Read entry 1356/7.4 as "1356 measurements conducted over a 7.4 year period"

Table 2. Mid-Latitude Site ($\epsilon_{STV} = 4.02 \times 10^{-2}$)

2-1  $\delta = 1.0 \times 10^{-3}$/yr     ($\pm 0.1\%$/year)
     $\lambda = 8.00 \times 10^{-1}$/day

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 1554/8.5 | 370/14.2 | 233/17.8 | 106/26.2 | 42/41.0 |
| 3 | 1800/9.9 | 429/16.4 | 271/20.7 | 123/30.4 | 49/48.0 |
| 5 | 2121/11.6 | 506/19.4 | 319/24.4 | 145/35.9 | 57/56.0 |
| 10 | 2998/16.4 | 715/27.4 | 450/34.5 | 205/50.9 | 81/80.0 |
| 20 | 4587/25.1 | 1094/41.9 | 689/52.8 | 314/78.0 | 124/123.0 |

2-2  $\delta = 2.0 \times 10^{-3}$/yr     ($\pm 0.2\%$/year)
     $\lambda = 8.00 \times 10^{-1}$/day

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 979/5.4 | 233/8.9 | 147/11.2 | 67/16.5 | 27/26.0 |
| 3 | 1135/6.2 | 271/10.3 | 170/13.0 | 78/19.2 | 31/30.0 |
| 5 | 1336/7.3 | 319/12.2 | 201/15.4 | 92/22.7 | 36/35.0 |
| 10 | 1885/10.3 | 450/17.2 | 284/21.7 | 129/31.9 | 51/50.0 |
| 20 | 2890/15.8 | 689/26.4 | 434/33.2 | 198/49.1 | 78/77.0 |

Table 2 (con't)

2-3  $\delta = 4.0 \times 10^{-3}$/yr  $(\pm 0.4\%/\text{year})$
     $\lambda = 8.00 \times 10^{-1}$/day

| $\varepsilon$INST (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 617/3.4 | 147/5.6 | 93/7.1 | 42/10.2 | 17/16.0 |
| 3 | 715/3.9 | 170/6.5 | 107/8.1 | 49/12.0 | 19/18.0 |
| 5 | 842/4.6 | 201/7.7 | 127/9.7 | 58/14.2 | 23/22.0 |
| 10 | 1190/6.5 | 284/10.8 | 179/13.7 | 82/20.2 | 32/31.0 |
| 20 | 1821/10.0 | 434/16.6 | 274/21.0 | 125/30.9 | 49/48.0 |

Table 3. Mid-Latitude Site ($\epsilon_{STV} = 4.02 \times 10^{-2}$)

3-1  $\delta = 1.0 \times 10^{-3}/\text{yr}$  ($\pm 0.1\%/\text{year}$)
$\lambda = 3.33 \times 10^{-2}\text{day}$

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 4215/23.1 | 605/23.2 | 308/23.5 | 110/27.0 | 42/41.0 |
| 3 | 4884/26.8 | 701/26.9 | 358/27.4 | 127/31.4 | 49/48.0 |
| 5 | 5754/31.5 | 827/31.7 | 421/32.2 | 150/37.1 | 57/56.0 |
| 10 | 8132/44.6 | 1169/44.8 | 594/45.5 | 212/52.5 | 81/80.0 |
| 20 | 12444/68.2 | 1788/68.6 | 909/69.7 | 324/80.6 | 124/123.0 |

3-2  $\delta = 2.0 \times 10^{-3}/\text{yr}$  ($\pm 0.2\%/\text{year}$)
$\lambda = 3.33 \times 10^{-2}/\text{day}$

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 2655/14.5 | 381/14.6 | 194/14.8 | 69/17.0 | 27/26.0 |
| 3 | 3078/16.9 | 443/17.0 | 224/17.1 | 81/19.8 | 31/30.0 |
| 5 | 3625/19.9 | 521/20.0 | 265/20.3 | 95/23.4 | 36/35.0 |
| 10 | 5114/28.0 | 736/38.2 | 375/28.7 | 133/33.0 | 51/50.0 |
| 20 | 7840/43.0 | 1126/43.2 | 573/43.9 | 205/50.7 | 78/77.0 |

Table 3 (con't)

3-3    $\delta = 4.0 \times 10^{-3}/\text{yr}$    $(\pm 0.4\%/\text{year})$
       $\lambda = 3.33 \times 10^{-2}/\text{day}$

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 1673/9.2 | 240/9.2 | 123/9.3 | 43/10.5 | 17/16.0 |
| 3 | 1940/10.6 | 278/10.6 | 141/10.8 | 51/12.4 | 19/18.0 |
| 5 | 2285/12.5 | 329/12.6 | 168/12.8 | 60/14.7 | 23/22.0 |
| 10 | 3226/17.7 | 464/17.8 | 236/18.0 | 85/20.9 | 32/31.0 |
| 20 | 4940/27.1 | 709/27.2 | 362/27.7 | 129/31.9 | 49/48.0 |

Table 4. Tropical Site ($\epsilon_{STV} = 2.10 \times 10^{-2}$)

4-1  $\delta = 1.0 \times 10^{-3}$/yr    (±0.1%/year)
     $\lambda = \infty$

|  |  | | $\Delta t$ (days) | | |
|---|---|---|---|---|---|
| $\epsilon_{INST}$ (%) | 2 | 14 | 28 | 91 | 365 |
| 0 | 879/4.8 | 240/9.2 | 151/11.5 | 69/16.9 | 27/26.3 |
| 3 | 1274/7.0 | 348/13.3 | 219/16.7 | 100/24.7 | 40/38.6 |
| 5 | 1655/9.1 | 452/17.3 | 285/21.8 | 130/32.1 | 51/50.4 |
| 10 | 2525/13.8 | 690/26.4 | 435/33.3 | 198/49.1 | 79/77.5 |
| 20 | 3965/21.7 | 1084/41.5 | 683/52.3 | 311/77.3 | 123/122.2 |

4-2  $\delta = 2.0 \times 10^{-3}$/yr    (±0.2%/year)
     $\lambda = \infty$

|  |  | | $\Delta t$ (days) | | |
|---|---|---|---|---|---|
| $\epsilon_{INST}$ (%) | 2 | 14 | 28 | 91 | 365 |
| 0 | 554/3.0 | 151/5.8 | 95/7.2 | 44/10.6 | 17/16.2 |
| 3 | 802/4.4 | 219/8.4 | 138/10.5 | 63/15.4 | 25/23.9 |
| 5 | 1043/5.7 | 285/10.9 | 180/13.7 | 82/20.1 | 32/31.4 |
| 10 | 1590/8.7 | 435/16.6 | 274/20.9 | 125/30.9 | 49/48.4 |
| 20 | 2498/13.7 | 683/26.1 | 430/32.9 | 196/48.6 | 78/76.6 |

Table 4 (con't)

4-3    $\delta = 4.0 \times 10^{-3}/\text{yr}$     $(\pm 0.4\%/\text{year})$

       $\lambda = \infty$                      $\Delta t$ (days)

| $\epsilon_{INST}$ (%) | 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 349/1.9 | 95/3.6 | 60/4.5 | 27/6.6 | 11/9.8 |
| 3 | 506/2.8 | 138/5.3 | 87/6.6 | 40/9.6 | 16/14.7 |
| 5 | 657/3.6 | 180/6.8 | 113/8.6 | 52/12.6 | 20/19.4 |
| 10 | 1002/5.5 | 274/10.5 | 173/13.2 | 79/19.3 | 31/30.1 |
| 20 | 1573/8.6 | 430/16.5 | 271/20.7 | 124/30.5 | 49/47.9 |

Table 5. Tropical Site ($\epsilon_{STV}$ = 2.10x10$^{-2}$)

5-1    $\delta$ = 1.0x10$^{-3}$/yr     ($\pm$0.1%/year)
        $\lambda$ = 8.00x10$^{-1}$/day

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 1007/5.5 | 240/9.2 | 151/11.5 | 69/17.0 | 27/26.0 |
| 3 | 1460/8.0 | 348/13.3 | 219/16.7 | 100/24.7 | 40/39.0 |
| 5 | 1897/10.4 | 452/17.3 | 285/21.8 | 130/32.2 | 51/50.0 |
| 10 | 2894/15.9 | 690/26.4 | 436/33.3 | 298/49.1 | 79/78.0 |
| 20 | 4544/24.9 | 1084/41.5 | 684/52.4 | 311/77.3 | 123/122.0 |

5-2    $\delta$ = 2.0x10$^{-3}$/yr     ($\pm$0.2%/year)
        $\lambda$ = 8.00x10$^{-1}$/day

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 635/3.5 | 151/5.8 | 95/7.2 | 44/10.7 | 17/16.0 |
| 3 | 919/5.0 | 219/8.4 | 138/10.5 | 63/15.5 | 25/24.0 |
| 5 | 1195/6.5 | 285/10.9 | 180/13.7 | 82/20.2 | 32/31.0 |
| 10 | 1822/10.0 | 435/16.6 | 274/21.0 | 125/23.5 | 49/48.0 |
| 20 | 2863/15.7 | 683/26.1 | 431/33.0 | 196/48.6 | 78/77.0 |

Table 5  (con't)

5-3  $\delta$ = 4.0x10$^{-3}$/yr  ($\pm$0.4%/year)
     $\lambda$ = 8.00x10$^{-1}$/day

| $\epsilon$INST (%) | $\Delta t$ (days) | | | | |
|---|---|---|---|---|---|
| | 2 | 14 | 28 | 91 | 365 |
| 0 | 400/2.2 | 95/3.6 | 60/4.5 | 27/6.5 | 11/10.0 |
| 3 | 580/3.2 | 138/5.3 | 87/6.6 | 40/9.7 | 16/15.0 |
| 5 | 753/4.1 | 180/6.8 | 113/8.6 | 52/12.7 | 20/19.0 |
| 10 | 1148/6.3 | 274/10.5 | 173/13.2 | 79/19.4 | 31/30.0 |
| 20 | 1803/9.9 | 430/16.5 | 271/20.7 | 124/30.7 | 49/48.0 |

Table 6. Tropical Site ($\epsilon_{STV}$ = 2.10x10$^{-2}$)

6-1    $\delta$ = 1.0x10$^{-3}$/yr     (±0.1%/year)
      $\lambda$ = 3.33x10$^{-2}$/day

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 2733/15.0 | 392/15.0 | 199/15.2 | 71/17.5 | 27/26.0 |
| 3 | 3960/21.7 | 569/21.8 | 289/22.1 | 103/25.5 | 40/39.0 |
| 5 | 5145/28.2 | 739/28.3 | 376/28.8 | 134/33.2 | 51/50.0 |
| 10 | 7849/43.0 | 1128/43.2 | 574/44.0 | 205/50.7 | 79/78.0 |
| 20 | 12326/67.5 | 1772/67.9 | 901/69.1 | 321/79.8 | 123/122.0 |

6-2    $\delta$ = 2.0x10$^{-3}$/yr     (±0.2%/year)
      $\lambda$ = 3.33x10$^{-2}$/day

| $\epsilon_{INST}$ (%) | $\Delta t$ (days) 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 1691/9.3 | 247/9.4 | 125/9.5 | 45/11.1 | 17/16.0 |
| 3 | 2493/13.7 | 358/13.7 | 182/13.9 | 65/16.0 | 25/24.0 |
| 5 | 3242/17.8 | 466/17.8 | 238/18.1 | 85/20.9 | 32/31.0 |
| 10 | 4943/27.1 | 711/27.2 | 362/27.7 | 129/31.9 | 49/48.0 |
| 20 | 7765/42.5 | 1116/42.8 | 568/43.5 | 202/50.2 | 78/77.0 |

Table 6 (con't)

6-3   $\delta$ = 4.0x10$^{-3}$/yr    (±0.4%/year)

     $\lambda$ = 3.33x10$^{-2}$/day      $\Delta t$ (days)

| $\epsilon$INST (%) | 2 | 14 | 28 | 91 | 365 |
|---|---|---|---|---|---|
| 0 | 1085/5.9 | 155/5.9 | 79/6.0 | 28/6.7 | 11/10.0 |
| 3 | 1573/8.6 | 226/8.6 | 115/8.7 | 41/10.0 | 16/15.0 |
| 5 | 2042/11.2 | 294/11.2 | 149/11.4 | 54/13.1 | 20/19.0 |
| 10 | 3115/17.1 | 448/17.1 | 228/17.4 | 82/20.1 | 31/30.0 |
| 20 | 4890/26.8 | 703/26.9 | 358/27.4 | 128/31.7 | 49/48.0 |

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APPENDIX C

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| 1. Report No. NASA CP-2362 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle Ozone Correlative Measurements Workshop | | 5. Report Date March 1985 |
| | | 6. Performing Organization Code GSFC/616 |
| 7. Author(s) Ernest Hilsenrath, Editor | | 8. Performing Organization Report No. 85B0183 |
| 9. Performing Organization Name and Address NASA/Goddard Space Flight Center Greenbelt, MD 20771 | | 10. Work Unit No. |
| | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 | | Conference Publication |
| | | 14. Sponsoring Agency Code Code EE |

15. Supplementary Notes
Scientific requirements, observational capability and recommendations for observing ozone trends in the atmosphere

16. Abstract
This Workshop was held to identify the observational needs to detect and verify ozone trends. Observations from the NOAA operational satellites will provide the global data set from which trends will be derived. The workshop concluded that correlative measurements were needed to validate the satellite observations and the results derived from those observations. The Workshop identified the scientific requirements for detecting trends and climatological studies. The capabilities of the satellite observations (mainly SBUV) and the existing correlative measurement techniques; e.g., ground based, balloon and rocket are reviewed. Satellite measurement validation was broken into two components; 1) Instrument performance verification and 2) algorithm verification. The recommended correlative measurement program followed from these two requirements. These recommendations include specific observational improvements of existing systems, development of ground based lidar, and the use of a Shuttle-borne SBUV. The Appendices deal with the number, frequency and precision of observations needed to verify the satellite data and to perform independent measurements to detect ozone trends.

| 17. Key Words (Selected by Author(s)) Ozone trends, Scientific Requirements, Satellite, rocket, balloon, ground based measurements | 18. Distribution Statement Star Category 42 Unclassified - Unlimited | | |
|---|---|---|---|
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No. of Pages 70 | 22. Price* A04 |