NAG5

CLIMATE SUITE STUDY REPORT

for the

NATIONAL POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM INTERNAL CONCEPTS STUDY

Part A:

OZONE SENSORS

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Executive Summary

1. Our recommendations to NPOESS for the sensors it should adopt to meet threshold requirements for global monitoring of ozone and, to some extent, of aerosols and of atmospheric temperature, pressure, and water vapor content are summed up in Table 1 on page 6. The degree to which these sensors fulfill other NPOESS requirements than ozone is summarized in Table 2, on page 9. The number of sensors that should be in the constellation is discussed in Section 2b, page 8, in terms of desired reliability, continuity of coverage, and the ability to cross-calibrate successive sensors.

2. Our recommendations for specific ozone measurement requirements, IORD item 4.1.6.2.28, are given on page 13.

3. In Section 4, pages 14 - 20, we make the case that monitoring of three minor constituents in the upper atmosphere (N_2O, ClO or $ClONO_2$, and HNO_3) should be added to the list of NPOESS requirements because of their importance to long-term ozone studies and the small additional cost required (ozone sensors are already designed to measure them). Specific measurement requirements, which should be regarded as supplementary to the ozone requirement, are given on pages 17 - 20.

4. The necessity of using two types of sensors - nadir-viewers and limb-scanners - for atmospheric studies is discussed in Section 5, pages 21 - 23.

Acknowledgement

Much information in this report was obtained from the NPOESS Ozone Measurement Requirements Workshop, held at the World Weather Building August 30 - 31. We would like to thank the attenders of the workshop for their inputs, with special thanks to Drs. L. Perlisky, R. Portmann, and D. Wuebbles for a substantial written contribution.

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Addresses the desireability of adding the minor stratospheric constituents N_2O, ClO or $ClONO_2$, and HNO_3 to the NPOESS requirements list.

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CLIMATE SUITE STUDY REPORT on OZONE SENSORS

1. Introduction

1a. Operational Satellite Data for Long-Term Ozone Studies

The application of NPOESS data to long-term studies related to climate changes is clearly evident when it is noted that of the 72 Environmental Data Records (EDRs) given in the Integrated Operational Requirements Document (IORD), 36 have defined climate applications. In the IORD, reference is made to the use of these 36 EDRs for validation of current models, as input to new climate models, and in studies of trends of certain geophysical parameters, especially ozone. In order to make optimum use of operational data in climate studies, requirements on data continuity and quality must be recognized and satisfied.

The importance of data continuity and quality are clearly demonstrated in the case of global ozone observations by satellite and other systems. Stratospheric ozone has been observed to decrease over the past two decades, a trend that is expected to persist into the next century. The data sets needed to determine this were assembled over the lifetimes of separate measurement systems. Continuity and quality of data had to be sufficiently good that an overall ozone record, rather than separate instrumental records, could be developed. As an <u>operational</u> system, NPOESS must provide data continuously, and long-term climate studies require data continuity over many years. This compatibility should not go unexploited.

NPOESS offers an extremely valuable opportunity to monitor and study the stratosphere's photochemistry and climate over a relatively long period in the next century. The fact that the number of research satellite launches in the next century is highly uncertain makes it essential that the planning for NPOESS be done as carefully and thoughtfully as possible. Special consideration needs to be given to accurate monitoring of ozone abundances, and to abundances of related minor species, in the upper troposphere and lower stratosphere. There are several reasons for this priority:

1) The observed changes in total ozone over the last twenty years have been due largely to decreases in lower stratospheric ozone. Over the next few decades, the significant stratospheric ozone decreases due to CFCs and halons are predicted to decline as stratospheric chlorine abundances begin to drop. However, recovery of the stratospheric ozone layer is not expected to be complete until the middle of the next century, and will be dependent on the actual production and emissions of HCFCs and other replacement compounds, the extent to which the Copenhagen Amendment to the Montreal Protocol is followed, and the amount of methyl bromide released into the atmosphere.

2) Recently, the effects of existing and projected aircraft emissions on upper tropospheric and lower stratospheric ozone have been the subjects of intense research. These potential effects are not well understood at this time, but are of sufficient concern to warrant increased emphasis on accurate ozone monitoring in these regions. In addition, extensive use of next-generation supersonic aircraft may begin around 2005, with probable flight altitudes in the 16-17 km altitude region, that is, in the lower stratosphere. While current models of atmospheric dynamical and photochemical processes do not project major changes in ozone from a fleet of as many as 500 of these HSCT aircraft, uncertainties in those models justify the need for monitoring of ozone in this region.

3) Several studies have shown that ozone changes in the upper troposphere and lower stratosphere (roughly 5-20 km) have the most significant impact on radiative forcing of climate change. Monitoring is needed to establish whether there are ozone trends in this region.

1b. Improving the NPOESS Requirements List

It is critical that the NPOESS program develop the ability to identify data issues as early as possible and provide a sense of priority to these issues. Without such an ability the shear magnitude of the issues for all of the 72 EDRs will inevitably lead to chaos, inaction, or at best disorganized action. Data are never perfect, so it is essential that the risk of inaction be closely linked to the environmental issues the data will be expected to address, both today and tomorrow. We suggest that serious consideration be given to those cases where NPOESS can measure important additional parameters at small additional cost. For ozone, the potential payoff is a large impact on future climate studies.

We have identified three minor constituents of the atmosphere, N_2O, ClO or $ClONO_2$, and HNO_3 , that are important adjuncts to long-term monitoring of ozone (the choice between ClO and $ClONO_2$ depends on whether a microwave or an infrared sensor is used). With these additional species, NPOESS data will be able to show not merely <u>that</u> ozone concentrations are changing in years to come, but also <u>why</u> they are changing. Since these constituents can be measured by the same instruments that measure ozone (in fact, most current ozone sensors have been built to measure some or all of them), adding this capability means only a small additional cost to NPOESS. The importance of these species to ozone studies is discussed in Section 4. In Sec. 2c, we also discuss the importance of stratospheric water vapor and aerosols for ozone studies and recommend that the currrent IORD requirement for these constituents be extended to higher altitudes.

2. Sensor Recommendations for Ozone Monitoring

2a. Sensor Types and Cost/Weight/Power Parameters

We recommend the sensors shown in Table 1 (next page) to fulfill threshold requirements for global monitoring of ozone. Sensors of both types 1 and 2 are, as explained in Section 5, necessary to meet NPOESS requirements for both horizontal and vertical resolution, respectively, with global coverage. A sensor of type 3 is <u>not</u> essential in this regard, but has the advantage of being "self-calibrating" and can therefore provide a valuable cross-check on the calibrations of the other sensors; furthermore, it is the only existing type of sensor that can measure aerosol profiles to altitudes as low as 5 km. A type-3 sensor is a light-weight, low-cost package and its use on NPOESS should be given serious consideration, especially if the NPOESS constellation will include any small satellites in lower-inclination (non-polar) orbits, because, as explained in Sec. 5b, its global coverage is thereby greatly improved. All of the sensors in Table 1 have a proven history of on-orbit operation.

Since sensors that measure ozone profiles (types 2 and 3 in the table below) must measure other atmospheric properties or species in order to infer ozone distributions (these are, depending on the sensor, temperature, pressure, and/or aerosols), some of these sensors will help to meet other NPOESS requirements directly, as indicated in Table 2 (page 9). They can also contribute indirectly by supplying information to Earth-observing NPOESS sensors that will help them to correct their observations for the effect of the intervening atmosphere.

Table 1. Ozone Sensors for NPOESS.

Sensors of types 1 and 2 are essential for fulfilling NPOESS ozone requirements.
A sensor of type 3 is optional for fulfilling NPOESS ozone requirements.

	1. TOMS/SBUV Derivative	2. Microwave Spectrometer (MAS/MLS-type)	or IR Limb-Scanner (HIRDLS-type)	3. Solar Occultation Sensor (SAGE or POAM type)
Coverage	Nadir-viewer, Global Daytime Coverage	Limb-scanner, Global Day/Night Coverage	Limb-scanner, Global Day/Night Coverage	Limb-scanner, Limited Global Coverage
Features	Direct Column Densities, Good Global Coverage, Long Legacy	Profile Measurements, 3 km Vertical Resolution, No Aerosol Problem	Profile Measurements, 1 km Vertical Resolution	Profile Measurements, 1 km Vertical Resolution, Minimal Calibration Problem
Size (cm)	50×70×20	170×130×120	130×90×80	70×30×20
Mass (kg)	45	120	75	25
Power (wt)	40	140	100	20
# on orbit[1]	1 or 2	1 - 3	1 - 3	1 or 2[2]
Cost 1st[3]	$12M	$11M	$22M	$8M
Cost 2nd[4]	$8M	$6M	$19M	$6M
Option Cost[5]	N/A	$2M	$2M	N/A

[1] Depends on available funding and cost vs. coverage/redundancy/reliability trade-offs

[2] More if lower-inclination satellites are added to the constellation

[3] Cost of first package, includes NRE

[4] Cost of packages after NRE

[5] Additional cost of monitoring minor constituents recommended in Sec. 4b, p. 14 - 20

Remarks on sensors in Table 1:

Type 1. The TOMS/SBUV series of sensors has been monitoring ozone column densities on a global scale since 1978, when the first TOMS sensor flew on NIMBUS-7. They have a long history of ozone measurements that should be continued by NPOESS. These sensors measure near-UV sunlight scattered from the atmosphere to determine the total column density of ozone. SBUV also gives some information on vertical distribution, but with very coarse resolution: 7 km at best, depending on altitude.

Type 2. Either a microwave spectrometer (MWS) or an IR limb-scanner (IRLS) is an obvious choice to achieve vertical resolution meeting NPOESS requirements. These sensors measure thermal radiation emitted by the atmosphere itself, hence are not limited to daylight observations and can provide more comprehensive global coverage. All other sensors discussed here observe sunlight, either scattered from the atmosphere or transmitted through it. An MWS has the further advantage that, because of the much longer wavelength of the detected radiation compared to optical/infrared sensors, its measurements are completely unaffected by aerosols. Consequently, it can maintain continuous observations even when the upper atmosphere is burdened by volcanic aerosols, as happened in 1991 when Mt. Pinatubo erupted.

Type 3. A solar occultation sensor (SOS) achieves excellent vertical resolution and has the least calibration problems of any remote-sensing ozone monitor. For both of these reasons, it can provide an important cross-check on the calibration of other sensors. Its global coverage is limited by the fact that it measures transmission of sunlight through the atmosphere, hence makes only about 28 observations per day (on orbital sunrises/sets); for polar orbits these observation points occur only near the north and south poles. Consequently, an SOS can beneficially be used on more than one satellite in the NPOESS constellation, especially if NPOESS plans to have any satellites in non-polar orbits (from a non-polar orbit, SOS observations are not restricted to the polar regions).

Further remarks on Table 1:

1) All costs are in 1995 dollars and are the costs to NPOESS for the complete sensor assembly, including program management by the executing agency. Spacecraft integration costs and post-launch support are not included, nor is software development for data processing.

2) Some versions of these sensors have already been built, so most development costs have been met, but there will still be some NRE (non-recurring engineering) charges to adapt the sensors to NPOESS needs and to incorporate technology improvements. This is especially true of the microwave spectrometer (MWS), for which the technology to use the 600 GHz region and an acousto-optic spectrometer will be proven in space on SWAS (Short-Wave Astronomy Satellite) in 1996.

3) Definite guidance is needed from NPOESS concerning the on-orbit lifetime and reliability specifications to which sensors should be built. Sensors are generally built to Class B standards at a minimum; if NPOESS desires full Class A standards to improve reliability over a 5-7 year life, costs may rise somewhat. Versions of most of these sensors are now on orbit and our knowledge of reliability will improve as time goes on.

2b. Data Continuity and Number of Sensors in Constellation

In order to monitor slow trends (e.g., in atmospheric ozone) with high reliability, it is important that, when a new satellite replaces an old one, the sensors on both be operated simultaneously for a substantial period of time: from six months to a year. Experience with the TOMS/SBUV series has shown the importance of checking on-orbit cross-calibrations in this manner - referred to as "cross-walk" - so that long-term data integrity can be maintained and long-term trends accurately monitored. "Cross-walking" is best done with sensors of the same type, but, if worst comes to worst, can still be at least partially effective with different types: if the sole TOMS/SBUV-type sensor fails and is not replaced for some period of time, data from an MWS or IRLS can help bridge the gap. Integrated profiles from the limb-scanner, averaged over large parts of the atmosphere, can partially substitute for, and be compared with, direct column-density measurements from the nadir-viewer (as discussed in Sec. 5a, the limb-scanner will not cover tropospheric ozone, but this usually makes only about a 10% contribution to the total column density).

For sensor types 1 and 2, careful consideration should be given to the importance of having at least one of each functioning on orbit at a given time. Of course sensors must be built to high standards, but a big gain in reliability can be had by flying redundant sensors. The most obvious way is to carry two identical sensors on the same satellite, with both operating continuously. Both could make complete observations, or global coverage could be divided half-and-half between the two. In the latter scheme, a single sensor must cover only half the globe, which means it can do so with better data quality due to the better signal-to-noise ratios resulting from longer integration times. Failure of one would, of course, double refresh times. NPOESS must make a cost/reliability trade-off to decide whether or not to fly two of each type of sensor simultaneously.

Two sensors on one satellite provide sensor redundancy but, of course, don't accomplish anything if the whole satellite fails. In general, mounting two sensors on different satellites provides greater reliability and shorter refresh times, but benefits depend on the sensor. A TOMS/SBUV-type sensor measures back-scattered sunlight and will function best on the 1330 satellite because, as seen from that satellite, sunlight impinges most directly on the atmosphere. It can also function, with somewhat degraded performance on the 0930 satellite (because sunlight impinges less directly on the atmosphere below, especially near the poles), but would not return much useful data on the 0530 satellite. Similarly, an SOS would function perfectly well on either the 1330 or 0930 satellites, but would be useless on the 0530 satellites where it would rarely see sunrises/sets. Both the MWS and the IRLS would function well on any of the satellites and consequently are good candidates for assuring continuity of coverage.

2c. Satisfaction of NPOESS Requirements

Table 2. Threshold Requirements Completely or Partially Addressed by Ozone Sensors. (More numbers in parentheses indicates greater deficiency.)

Sensor Type:	TOMS/ SBUV	IRLS & MWS	Solar Occultation
Parameter			
Key			
4.1.6.1.1 Vertical moisture profile*		P(1,2)	P(1,2,3)
4.1.6.1.2 Vertical temperature profile		P(1,2)	P(1,2,3)
Other			
4.1.6.2.1.1 Aerosol partical size		IR: P(1,2,3)	P(1,2,3)
4.1.6.2.1.2 Aerosol optical thickness		IR: P(1,2,3)	P(1,2,3)
4.1.6.2.28 Ozone column	C	P(1)	S(3)
4.1.6.2.28 Ozone profile	P(4)	C	S(3)
4.1.6.2.31 Pressure profile		P(1,2)	P(1,2,3)
4.1.6.2.41 Total water content		P(1,2)	P(1,2,3)

* Usually, but not always, measured by ozone profile sensors

C = Complete satisfaction of requirement
S = Significant satisfaction of requirement
P = Partial satisfaction of requirement

1 = Measures upper troposphere and above only
2 = Inadequate horizontal resolution
3 = Inadequate global coverage or refresh time
4 = Inadequate vertical resolution

Table 2 gives our estimates of the degree to which the proposed ozone sensors satisfy current NPOESS requiements. But measuring the Earth's atmosphere is not a simple matter and these estimates should not be strictly interpreted. The "complete" grade given to a TOMS/SBUV-type sensor for the ozone column density requirement is basically accurate, but should be qualified by the fact that, since it measures solar UV radiation scattered from the atmosphere, its performance is degraded in those regions near the north and/or south poles (depending on time of the year) where sunlight enters the atmosphere at off-zenith angles greater than about 80°. During the polar night, of course, it doesn't enter at all. Also, the attribution of "global" coverage to limb-scanning sensors means that they sample many thousands of points in the atmosphere, distributed in latitude and longitude, in the course of a day, but do not completely blanket the Earth. These points are discussed in somewhat more detail in Section 6a.

The non-ozone requirements listed in Table 2 as being partly addressed by limb-scanning ozone sensors (MWS, IRLS, or SOS) fall into two categories: things that the sensors must measure in order to infer the concentration of ozone (temperature and pressure profiles and aerosol properties) or that the sensors can, and existing sensors do, measure with small additional cost.

Things in the first category (aerosols, temperature, pressure) must be measured so that their contributions to the ozone signal can be corrected for. Aerosols are measured directly by their light-scattering properties by an IRLS or SOS; as previously noted, an MWS is insensitive to aerosols. It is important to note that an SOS is the only existing sensor that can measure aerosol profiles down as low as 5 km. MWS and SOS sensors determine temperature and pressure profiles by measuring the concentration of normal oxygen, O_2 , in the same manner (thermal emission or absorption of sunlight) that is used to measure O_3 . Since the fraction of the atmosphere that is O_2 is known and constant (21% by volume), knowledge of O_2 gives density. The sensors scan vertically, hence give density as a function of altitude, information that can be combined with the ideal gas law and the fact that the atmosphere is in hydrostatic equilibrium to yield pressure and temperature profiles. IRLS sensors perform the same function by measuring CO_2.

Things in the second category are relatively easy to measure with the same sensor that measures ozone, and are of sufficient interest that they have been included, to a greater or lesser extent, in all limb-scanning ozone sensors built to date. The principle constituent of interest to NPOESS is water vapor (which, of course, contributes to total water content). The other constituents of concern are those recommended in Section 4 (N_2O, ClO or $ClONO_2$, HNO_3) as being important to monitoring the why, as well as the how, of long-term ozone trends. These constituents can be added to the NPOESS requirements list for a small increment in cost.

The shortcommings of limb-scanning sensors, from the point of view of fulfilling other NPOESS requirements than ozone, is that they are generally limited to altitudes above about 5 - 10 km, have poor horizontal resolution, and, in the constellation proposed here, do not have refresh times less than a few days (these points are discussed in more detail in Section 6a). But good horizontal resolution and short refresh times are far less important in the stratosphere than in the troposphere. Thus, these sensors can partially meet IORD requirement 4.1.6.1.2 for vertical temperature profiles by covering the stratosphere above about 300 mb (about 9 km, i.e., the tropopause), as long as it is recognized that horizontal resolution need be no better than a few hundred kilometers in that region and that refresh times of only a few hours are unnecessary. This may simplify the design of the sensor that is built to satisfy the rest of the requirement. The same remarks apply to requirement 4.1.6.1.1 for moisture profiles, if it is extended above the currently-stated limit of 100 mb (about 15 km).

It is important to note that an IRLS can be built to remove the restriction on refresh times given above (by azimuth scanning, this is discussed in Section 6a). Such an instrument, if flown on all three satellites, could give upper-tropospheric and stratospheric profiles for temperature, water vapor, and aerosols with refresh times not exceeding 8 hours and possibly as short as 4 hours.

Stratospheric water vapor

The current NPOESS requirement for water vapor (IORD item 4.1.6.1.1) extends only to an altitude of about 15 km (100 mb). Of course monitoring water vapor in the upper troposphere (altitudes greater than 5 km) is extremely important to improving the current understanding of the climate system and its potential future changes. The amount of water vapor in this region and its response to climate changes is an uncertain, but important, element in improving the models being used to study climate. In addition, measurements of water vapor in this region are useful as an indicator of possible changes in the transport of water vapor into the stratosphere due to changes in tropospheric circulation. But long-term measurement of <u>stratospheric</u> water vapor is also a high priority

Changes in stratospheric water vapor affect heterogeneous chemical processes and, therefore, stratospheric ozone loss rates in the lower stratosphere by affecting the formation rate of polar stratospheric clouds (PSCs), changing the composition of stratospheric aerosols, and acting as a source of reactive hydrogen. Photochemistry involving hydrogen radicals is very important because nitrogen and halogen ozone-destruction cycles are effectively modulated by formation of reservoir species such as HNO_3 and HCl. Ozone is also catalytically destroyed by hydrogen-containing atmospheric trace species, and these cycles are currently thought to dominate ozone loss in the mid-latitude lower stratosphere and the sunlit upper stratosphere. Therefore it would be of interest to monitor long-term changes in stratospheric water vapor, which is expected to increase due to increasing methane abundances.

We therefore recommend that the NPOESS water vapor monitoring requirement (IORD # 4.1.6.1.1) be extended to 40 - 60 km. The sensors recommended here can satisfy this requirement.

Stratospheric aerosols

Stratospheric aerosols are important from an ozone-studies standpoint because they play a key role in the partitioning between unreactive reservoir forms and reactive species which destroy ozone. Heterogeneous reactions of the reservoir molecules $ClONO_2$, N_2O_5, HCl, and $BrONO_2$ on the surface of stratospheric aerosols effectively convert unreactive chlorine and bromine to reactive forms while cycling nitrogen to HNO_3, a sink for reactive stratospheric nitrogen. These heterogeneous processes are very temperature-dependent and tend to occur fastest at cold temperatures. However, heterogeneous chemistry is thought to be relatively efficient on stratospheric liquid aerosols particles (composed of a solution of sulfuric acid in water) as well as on PSC particles. The presence of the background sulfate aerosol layer in the stratosphere has likely contributed to the long-term ozone decrease at mid-latitudes due to increases in atmospheric chlorine and bromine. In addition, enhanced aerosol abundances due to volcanic eruptions cause large ozone depletion events, as observed after the eruptions of El Chichon in 1982 and Pinatubo in 1991. The aerosol loading of the lower stratosphere has been highly variable during the period from the late '70s (when satellite aerosol measurements began) and the present, and will likely remain so in the future. Direct measurement from satellite currently remains the only reliable way to obtain global estimates of stratospheric aerosol surface area and attendant effects on ozone.

A further argument for long-term monitoring of stratospheric aerosols is that, although stratospheric ozone is expected to recover in the next century due to atmospheric halogen decreases, several factors could slow or even reverse this recovery. The stratosphere could cool, for example, as the troposphere warms due to increased carbon dioxide. A stratospheric cooling would accelerate the temperature-dependent heterogeneous conversion of nonreactive to reactive chlorine and bromine, and likely increase the frequency of PSC formation, perhaps accelerating lower stratospheric ozone loss at high latitudes. Another possibility is that the properties of the stratospheric aerosol layer itself could exhibit long-term behavior. Ground-based observations suggest that the sulfate aerosol abundance in the stratosphere may be increasing due to anthropogenic sulfur emissions. Stratospheric water vapor increases are also expected in the future, due to atmospheric methane increases. Both of these factors will likely change the characteristics of the stratospheric aerosol layer, including the composition of the aerosols (which affect the rate at which heterogeneous chemistry occurs) and, possibly, the frequency of PSCs.

We recommend that the NPOESS aerosol monitoring requirement (IORD # 4.1.6.2.1) be extended to 30 - 40 km. The SOS sensors recommended herein can then help to satisfy this requirement. As explained briefly in Sec. 5b, an SOS is the only existing sensor that can measure aerosol profiles from the highest altitudes at which they are significant to altitudes as low as, or lower than, 5 km.

3. Ozone Requirements Recommendations for NPOESS IORD

The goal of the recent NPOESS Ozone Measurement Requirements Workshop, held at the World Weather Building, August 30 - 31, was to achieve a consensus on ozone measurement parameters, such as accuracy and resolution, to fill in the many TBDs in the existing IORD listing (Sec. 4.1.6.2.28). The consensus arrived at is shown on the next page. Among the eminent authorities on ozone who attended were Drs. J. Angell, K. Bowman, E. Hilsenrath, L. Hood, J. Kaye, R. Portmann, L. Perlisky, E. Remsberg, E. Shettle, R. Stolarski, and D. Wuebbles. This workshop was very successful, and it is our opinion that more such events should be held in order to ensure the maximum amount of scientific involvement in planning the NPOESS program.

It is very difficult to come up with a set of measurement parameters without considering what types of instruments could fill the requirements. Currently, the research community is supposed to recommend parameters of the system without considering the type of instrument that would best fill the requirements. The prospective contractors are then expected to propose a specific observing system which may be rejected if it does not meet the stated requirements. At first this methodology may seem perfectly rational, but it may be argued that the choice of the type of instrument should not be separated so remotely from the original scientific considerations.

A better way to proceed is to discuss past ozone measurement systems, carefully evaluating and comparing them in the context of their appropriateness for an operational satellite program. Scientists intimately familiar with successful instruments such as TOMS, SBUV, LIMS, SAGE, and MLS should discuss the advantages and weaknesses of the these systems in detail. Let's try to learn as much as possible from our past experiences! In addition, the possibility of using the proposed instrument to measure other stratospheric parameters (as discussed in Sections 2c and 4) should also be weighed, since it is possible that additional atmospheric information could be obtained very economically. This would increase the likelihood that we will get the most scientifically-useful measurements possible for the first half of the next century.

4.1.6.2.28 Ozone Total Column/Profile (DoC).

Systems Capabilities		Thresholds	Objectives
a. Sensing Depth			
1. Total Column		0 - 100 km	0 - 100 km
2. Profile		10 - 60 km	0 - 60 km
b. Horizontal Resolution			
1. Total Column		50 km at nadir[1]	50 km[2]
2. Profile		500 km	250 km
c. Vertical Resolution			
1. Total Column		N/A	N/A
2. Profile	0 - 10 km:	N/A	3 km
	10 - 25 km:	3 km	1 km
	25 - 60 km:	5 km	3 km
d. Mapping Accuracy			
1. Total Column		5 km	5 km
2. Profile		40 km	25 km
e. Measurement Range			
1. Total Column		0.05 - 0.65 atm-cm	0.05 - 0.65 atm-cm
2. Profile	0 - 10 km:	N/A	0.01 - 3 ppmv (10^{11} - 3×10^{12} cm^{-3})
	10 - 60 km:	0.1 - 15 ppmv (3×10^{9} - 10^{13} cm^{-3})	0.1 - 15 ppmv (3×10^{9} - 10^{13} cm^{-3})
f. Measurement Precision			
Short term[3]: 1. Total Column		0.001 atm-cm	0.001 atm-cm
2. Profile	0 - 10 km:	N/A	10%
	10 - 15 km:	10%	3%
	15 - 50 km:	3%	1%
	50 - 60 km:	10%	3%
Long term[4]: 1. Total Column		1%	0.5%
2. Profile		2%	1%
g. Measurement Accuracy[5]			
1. Total Column		0.015 atm-cm	0.005 atm-cm
2. Profile	0 - 10 km:	N/A	10%
	10 - 15 km:	20%	10%
	15 - 60 km:	10%	5%
h. Refresh			
1. Total Column		1 day	1 day
2. Profile		7 day	1 day

[1] May increase as necessary toward edge of swath.

[2] Constant across swath.

[3] Instantaneous repeatability (due to noise).

[4] Calibration stability over life of sensor.

[5] Includes uncertainties in line strengths, not just instrumental uncertainties.

Remarks on ozone requirements table:

Item a. The threshold requirement for the altitude range of ozone profiles is 10 km and above. High vertical resolution requires limb-scanning sensors, but limb-scanners cannot, except on rare occasion and depending on the sensor, probe the atmosphere down to the surface. The ultimate requirement objective, as opposed to the threshold requirement, for high vertical resolution at all altitudes cannot be met with existing sensors. One reason for this is that a cloud-free line of sight (LOS) exceeding several hundred kilometers is required (for a limb-scanner, the LOS traverses over 500 km horizontally in probing the lower-most 5 km of the atmosphere). Another limiting factor for MWS and IRLS sensors is that the spectral lines they use become saturated in the lower atmosphere. The result is that limb-scanning sensors should be regarded as effective only in the stratosphere and, to some extent, the upper troposphere. (The dividing line between the two, the tropopause, is generally around 8 - 10 km.) Usually, only about 10% of all atmospheric ozone is in the troposphere, though this may rise as high as 25% in the tropics during September and October, due to anthropogenic biomass burning.

Item c. Vertical resolution of ozone profiles in the three atmospheric layers indicated are based on how ozone concentrations change in the layers. Best resolution is called for in the 10 - 25 km layer, where ozone concentrations change most rapidly.

Item d. Mapping accuracy, which refers to knowledge of the location of the observed point (the center of a pixel for a nadir-viewer or location of the tangent point for a limb-scanner), is specified as one-tenth of horizontal resolution. This factor-of-ten disparity between horizontal position accuracy and horizontal position resolution is chosen to facillitate data comparisons and because it should not be difficult to achieve.

Item f. Measurement precision is separated into short- and long-term requirements because of the necessity of maintaining good long-term calibration stability for climate studies.

Item h. For stratospheric ozone profiles, the threshold refresh time of 7 days is acceptable from a climate studies standpoint. In this context, the term refresh time means the time over which a dense set of sample points is assembled, rather than the time required to "paint" the Earth. This point is discussed in more detail in Sec. 6a.

4. Recommendations for Additional NPOESS Requirements

A thorough understanding of ozone creation, depletion, and long-term trends requires detailed studies of many chemical processes, especially, for example, those that contribute to catalytic cycles of ozone production and loss. These process studies do not demand data from a global, operational system such as NPOESS - they are best left to dedicated research satellites (such as UARS) that are designed to give specialized data for detailed scientific analysis. Operations and research must maintain a common interface in atmospheric measurements. The vital role that NPOESS can play is to provide continuous, long-term monitoring of those particular constituents that these research studies have shown to be good "marker" species. The ability to interpret ozone measurements accurately will be considerably diminished without corresponding measurements of those trace constituents that are critical in influencing ozone levels.

The question of what these constituents should be was addressed in the Ozone Measurement Requirements Workshop. Aerosol abundances and stratospheric water vapor are very important, as discussed in Sec. 2c. While a detailed consensus was not arrived at on what trace molecular species should be monitored, the following are provisional candidates: N_2O, ClO or $ClONO_2$, and HNO_3 . These species are involved in the partitioning of chlorine between reactive and reservoir forms, in other aspects of the catalytic cycles that destroy ozone, and, in the case of N_2O, provide vital information on atmospheric transport dynamics. For example, continuous global monitoring of ClO can be used to derive the total chlorine loading of all parts of the upper atmosphere. Thus, if monitoring these constituents can be added to NPOESS requirements, then NPOESS data will be able to show not merely that ozone concentrations are changing in years to come, but also why they are changing. The capability of measuring these constituents can be added to an MWS or an IRLS at a small additional cost, as indicated in Table 1 (page 6).

The choice between ClO or $ClONO_2$ depends on whether an MWS (ClO) or an IRLS ($ClONO_2$) is used, but we should emphasize that ClO is strongly preferred over $ClONO_2$, for the reasons given below. Measurement of HNO_3 is very difficult to do with an MWS. The low line strength means that many profiles must be averaged together to obtain good SNRs, and that means that only very coarse horizontal resolution can be obtained.

N_2O (nitrous oxide)

Since the rate at which lower stratospheric ozone destruction occurs is controlled by such meteorological parameters as temperature and solar insolation, understanding the role of atmospheric dynamics and transport is essential to prediction of ozone loss. Measurements of N_2O provide a very good diagnostic of atmospheric transport because it is a long-lived trace species. Since it has a net source at the Earth's surface, and is destroyed by photolysis and reaction with O(1D) (which is itself a product of O_3 photolysis) in the upper stratosphere, N_2O has been successfully used for such applications as defining the polar vortex and tropical boundaries. In addition, comparisons of N_2O measurements with model calculations has provided an excellent opportunity to assess the fidelity of modeled atmospheric circulation and transport to the real atmosphere. Long-term observations of N_2O would enable the community to monitor atmospheric circulation trends, and would be of considerable scientific interest since no long-term observations of a dynamical tracer as good as N_2O currently exist.

In addition to being a transport diagnostic, N_2O also plays a role in stratospheric ozone abundance because it is a principal source of reactive nitrogen molecules (NO_X) that participate directly in the catalytic destruction of ozone.

ClO (chlorine monoxide) or $ClONO_2$ (chlorine nitrate)

There is overwhelming evidence that chlorine compounds are largely responsible for the ozone depletion from the mid-seventies to the present, and they are predicted to continue to deplete ozone until they decline to background levels sometime in the middle of the next century.

The monitoring of ClO will allow the direct estimation of chlorine-induced ozone loss because it participates directly in the catalytic destruction of ozone. This will be extremely valuable for identifying ozone loss processes and for estimating the degree of chemical processing at polar latitudes. Monitoring of $ClONO_2$ is less desireable because, while it serves as a reservoir species for chlorine in the stratosphere, it does not directly participate in ozone-destroying reactions. However, an IRLS cannot measure ClO, so, if such an instrument is chosen, $ClONO_2$ becomes the best chlorine compound for monitoring.

HNO_3 (nitric acid)

HNO_3 plays a vital role in the formation of polar stratospheric clouds and it is on the surface of these cloud particles that many chemical reactions take place ("heterogeneous chemistry") that contribute to ozone destruction, e.g., the conversion of nonreactive to reactive halogen-containing molecules. In the lower stratosphere, HNO_3 is another source, besides N_2O, of NO_x . As a reservoir species for nitrogen, HNO_3 is also important in monitoring trends in nitrogen-containing compounds due to increases in surface nitrogen sources and aircraft emissions.

Specific measurement requirements for these species are given in tabular form on the next four pages. We believe these tables to be reasonable, but, unlike the ozone requirements table on p. 13, they have not been subjected to peer review. These are requirements for species profiles, hence can be met only with limb-scanning sensors; column densities of these species, besides being very difficult to measure, would not be very useful. The listed requirements are based on the table for ozone (p. 13) because the same sensor will be used to measure them. Numbers have been adapted to the particular species where appropriate.

4.1.6.2.28a Ozone-related minor constituent: N_2O profile.

Systems Capabilities		Thresholds	Objectives
a. Sensing Depth		10 - 50 km	10 - 60 km
b. Horizontal Resolution		500 km	250 km
c. Vertical Resolution	10 - 25 km:	3 km	1 km
	25 - 60 km:	5 km	3 km
d. Mapping Accuracy		50 km	25 km
e. Measurement Range		5 - 400 ppbv 5×10^7 - 4×10^{12} cm^{-3}	1 - 400 ppbv 10^7 - 4×10^{12} cm^{-3}
f. Measurement Precision			
Short term[1]:		10%	5%
Long term[2]:		5%	2%
g. Measurement Accuracy[3]		30%	5%
h. Refresh		7 day	1 day

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[1] Instantaneous repeatability (due to noise).

[2] Calibration stability over life of sensor.

[3] Includes uncertainties in line strengths, not just instrumental uncertainties.

4.1.6.2.28b for MWS: <u>Ozone-related minor constituent: ClO profile</u>.

Systems Capabilities		Thresholds	Objectives
a. Sensing Depth		15 - 50 km	15 - 50 km
b. Horizontal Resolution		1000 km	250 km
c. Vertical Resolution	10 - 25 km:	3 km	1 km
	25 - 60 km:	5 km	3 km
d. Mapping Accuracy		100 km	25 km
e. Measurement Range	15 - 50 km:	0 - 3 ppbv	0 - 3 ppbv
f. Measurement Precision			
Short term[1]:		0.1 ppbv	0.05 ppbv
Long term[2]:		0.2 ppbv	0.05 ppbv
g. Measurement Accuracy[3]		0.2 ppbv	0.05 ppbv
h. Refresh		7 day	1 day

---

[1] May include effect of averaging profiles over horizontal region indicated in b.

[2] Calibration stability over life of sensor.

[3] Includes uncertainties in line strengths, not just instrumental uncertainties.

4.1.6.2.28b for IRLS: Ozone-related minor constituent: $ClONO_2$ profile.

Systems Capabilities		Thresholds	Objectives
a. Sensing Depth		15 - 35 km	15 - 40 km
b. Horizontal Resolution		1000 km	250 km
c. Vertical Resolution	10 - 25 km:	3 km	1 km
	25 - 60 km:	5 km	3 km
d. Mapping Accuracy		100 km	25 km
e. Measurement Range	15 - 25 km:	0 - 3 ppbv	0 - 3 ppbv
	25 - 40 km:	0 - 2 ppbv	0 - 2 ppbv
f. Measurement Precision			
Short term[1]:		0.1 ppbv	0.05 ppbv
Long term[2]:		0.2 ppbv	0.05 ppbv
g. Measurement Accuracy[3]		0.2 ppbv	0.05 ppbv
h. Refresh		7 day	1 day

[1] May include effect of averaging profiles over horizontal region indicated in b.

[2] Calibration stability over life of sensor.

[3] Includes uncertainties in line strengths, not just instrumental uncertainties.

4.1.6.2.28c Ozone-related minor constituent: HNO_3 profile.

Systems Capabilities		Thresholds	Objectives
a. Sensing Depth		10 - 50 km	10 - 60 km
b. Horizontal Resolution		1000 km	250 km
c. Vertical Resolution	10 - 25 km:	3 km	1 km
	25 - 60 km:	5 km	3 km
d. Mapping Accuracy		100 km	25 km
e. Measurement Range			
	10 - 35 km:	1 - 20 ppbv	1 - 20 ppbv
	35 - 50 km:	0.5 - 10 ppbv	0.2 - 10 ppbv
f. Measurement Precision			
Short term[1]:		1 ppbv	0.1 ppbv
Long term[2]:		2 ppbv	0.2 ppbv
g. Measurement Accuracy[3]		2 ppbv	0.5 ppbv
h. Refresh		7 day	1 day

[1] May include effect of averaging profiles over horizontal region indicated in b.

[2] Calibration stability over life of sensor.

[3] Includes uncertainties in line strengths, not just instrumental uncertainties.

5. Nadir-viewing and Limb-scanning Sensors for Atmospheric Studies

5a. General Considerations

Earth-surface studies generally require only one type of sensor to achieve high spatial resolution because the Earth's surface is essentially two-dimensional. But atmospheric studies are necessarily three-dimensional, and NPOESS requirements for good horizontal and vertical resolution cannot be met without using the two classes of sensors, nadir-viewers and limb-scanners, illustrated in Figure 1. Good horizontal resolution requires nadir-viewers, for which the LOS intersects the surface of the Earth and which are pointed primarily in the nadir direction (though they may scan far enough off nadir to come near the horizon). Good vertical resolution requires limb-scanners, for which the LOS is directed just above the horizon (the "limb" in astronomical parlance) and does not intersect the hard Earth, except perhaps at the lower end of the scan. For atmospheric studies, the two types of sensors perform vital complementary functions.

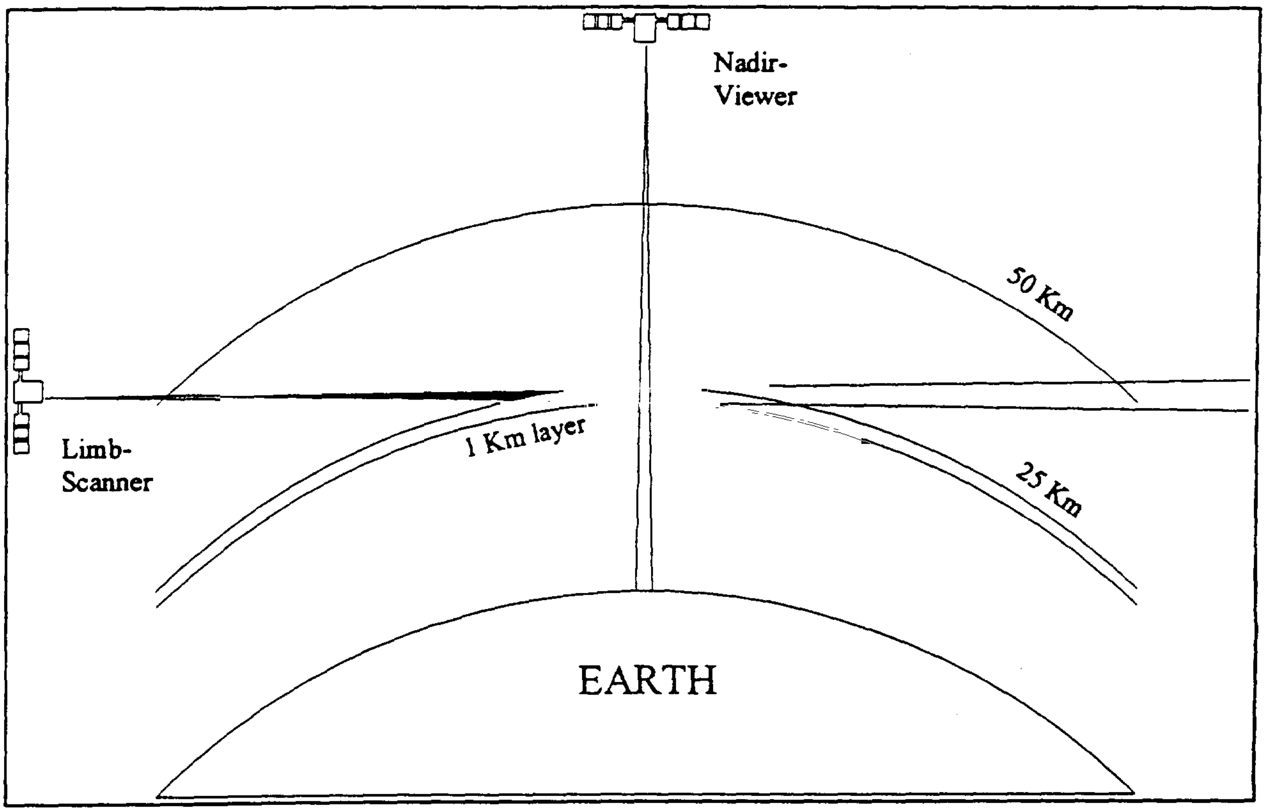


Figure 1. Illustrating nadir-viewing and limb-scanning atmospheric sensors. For an assumed atmospheric depth of 50 km, a 1 km-thick layer (here at 25 km altitude, typically about the peak concentration of ozone) occupies about 14% of the LOS of a limb-scanning sensor, but only 2% of the LOS of a nadir-viewer.

As can be seen from Fig. 1, nadir-viewers can (1) directly measure integrated column densities and (2) easily achieve good horizontal resolution, simply by using a sensor with a narrow field of view (FOV). They have a much harder time, however, in measuring vertical profiles. Usually, this is done by making measurements, with high spectral resolution, of an absorption feature - a line or an edge - and using subtle variations in the shape of this feature to infer the altitude dependence of the species in question. Nadir-viewers are severly hampered in this process by the fact that the measured signal is a sum of the signals from all altitudes at once, which means that the signal from a particular atmospheric layer may contribute only a very small fraction of the total signal, and hence be hard to determine. The higher the vertical resolution desired, the more severe this problem becomes because more independent measurements at different wavelengths, with higher spectral resolution and better signal-to-noise ratio (SNR), are required.

Limb-scanners, on the other hand, easily achieve good vertical resolution, simply by using a sensor with a narrow field of view. The difficulty of separating out different layers of the atmosphere is less severe than for nadir-viewers because (1) the signal comes disproportionately from the lowest layer in the part of the atmosphere traversed by the LOS, and (2) the LOS scans the limb vertically, thereby assuring that all parts of the atmosphere will at some point in the scan constitute the lowest layer. In the example shown in Fig. 1, a 1 km-thick layer occupies only 2% of the LOS from a nadir-viewer, but about 14% for a limb-scanner. The shortcoming of limb-scanners is that they cannot achieve good horizontal resolution. This is inherently true along the LOS, which spends about 250 km traversing a 1 km layer. Good horizontal resolution across (i.e., perpendicular to) the LOS is possible, but that alone is rarely, if ever, useful. The other disadvantage of limb-scanners is that, as discussed in Sec. 2c, their observations are generally limited to altitudes above about 5 km (the upper troposphere and above). They can only rarely make obsevations in the lower troposphere, partly because the increasing optical depth through the atmosphere attenuates the signal too much, but mostly because cloud-free horizontal lines of sight exceeding 500 km are required.

5b. Solar Occultation Sensors

Solar occultation sensors (SOSs) constitute an important subclass of limb-scanning sensors. An SOS views the Sun through the Earth's atmosphere and detects atmospheric species by the degree to which they absorb sunlight in particular bands of the visible, infrared, or ultraviolet spectrum. In Fig. 1, the limb-scanning sensor could be an SOS observing the Sun as it rises or sets through the atmosphere, as seen from the satellite. Good vertical resolution is obtained by focusing an image of the Sun onto a small aperture (usually a narrow horizontal slit), and measuring only the light that passes through this aperture. 1 km vertical resolution can easily be achieved in this manner. Because the Sun is a very bright source, only small collecting optics and a simple instrument are needed to obtain excellent signal-to-noise ratios. A great advantage of this technique is that it is "self-calibrating": the unattenuated Sun is measured when it stands clear of the atmosphere, and this signal is used to calibrate the through-the-atmosphere measurements taken a minute or two earlier or later. Thus, biases or slow changes in the sensor do not affect the results.

It happens that the spectral lines that the SOS sensors detect by transmitted sunlight generally have less optical thickness than those that the other limb-scanners (MWS and IRLS) detect by emitted (thermal) radiation. This means that the SOS sensors can more easily probe lower altitudes than the others. The limiting factor is the presence of clouds: if the LOS is cloud-free, an SOS can probe right down to the surface. But in order to do this, the LOS must spend over 500 km traversing the troposphere, and it is rare to have such a long cloud-free path. SAGE routinely measures aerosols down to 10 km and often down to 5.

The disadvantage of an SOS, as shown in detail in Section 6, is its sparse global coverage: only two occultations can occur per orbit (on orbital sunrise and sunset), or about 28 per day. Further limiting coverage is the fact that, for polar orbits, these events can occur only within about 50° of the poles (but these are important regions where the greatest depletion of global ozone is found). Coverage can be considerably enhanced if SOSs can be placed on satellites with lower-inclination orbits: if NPOESS plans to have any such satellites, serious consideration should be given to flying SOSs on them. The problem of sparse coverage by an SOS is being partially allievated in the design of the latest SAGE sensor, SAGE III, which will have sufficient sensitivity to perform atmospheric measurements using the Moon as well as the Sun. This will provide some additional coverage for 10 - 15 nights each month. Because the Moon's motion around the Earth is much different from the Sun's, some of these measurements will take place at temperate latitudes instead of near the poles.

Even though SOSs provide only sparse global coverage, they can still be of value to NPOESS because, being self-calibrating, they provide a vital calibration check on other sensors. A TOMS/SBUV ozone sensor, for example, can provide dense global coverage, but is hard-pressed to maintain good absolute calibration over a period of years. On a daily basis, however, it will cover the same parts of the atmosphere viewed by the SOS, and the self-calibrated vertical profile derived from the latter can be integrated vertically to check total column measurements of the former. This will greatly improve the sensors' abilities to satisfy NPOESS requirements for monitoring gradual, long-term trends in ozone concentration. Nadir-viewers can also add to the information obtained by limb-scanners. To some extent, having column-density observations in regions surounding the points measured directly by a limb-scanner will enhance our ability to infer profiles in those regions.

6. Orbitology and Global Coverage

6a. Nadir-Viewers and Non-SOS Limb-Scanners

An important NPOESS parameter is refresh time, which means the time between one complete coverage of the globe and the next. We need to address the question of how dense global coverage must be. Must every portion of the globe fall within a sensor's FOV within a refresh time, or not? For observations of the Earth's surface or of the troposphere the answer to this question is generally yes: because of the fine structures of these regions - from kilometers down to meters - coverage needs to be dense to be considered truly global. For important weather-related phenomena such as winds, clouds, and atmospheric water content, refresh times measured in hours are very desireable. But stratospheric structures tend to be large scale, hence do not have to be sampled at close intervals, and for ozone monitoring, especially from a climate studies standpoint, refresh times measured in days, rather than hours, are acceptable. We must now justify our choices, given on p. 13, of 1 day refresh time for monitoring ozone column densities and 7 for stratospheric ozone profiles.

Since the column density sensor is a nadir-viewer, it probes into the troposphere, hence must observe all parts of the atmosphere every 24 hours because of tropospheric variability. It must therefore completely cover a ground swath 2800 km wide on each pass. At the outer edge of this swath, 1400 km from the ground track, the sensor's LOS traverses the atmosphere at an angle of 70° from the zenith. At that angle the sensor's horizontal footprint is increased by a factor of about 2 in the direction across the LOS and a factor of about 6 in the direction along it. In other words, if the footprint was 50×50 km at nadir, it is now 100×300 km, a fact reflected in the threshold requirement for horizontal resolution given on page 13.

Unlike the troposphere, where the state of the atmosphere may be very different in places separated by only a few kilometers, the stratosphere tends to be much more uniform. In the upper stratosphere (around 20 km and above) structural scales are generally hundreds or thousands of kilometers. Detailed examination will, of course, show some low-level structure on any distance scale, but these are not of prime importance for climatological monitoring of ozone profiles. This means that monitoring can be effective even if every point in the stratosphere does not fall within the field of view of a sensor within a short period of time. It is necessary only that sample points in the stratosphere be dense enough so that no significant structures are missed.

For a polar-orbiting satellite, the least dense coverage occurs at the equator, where a day/night sensor makes 28 observations per day (two equator crossings per orbit, 14 orbits per day), spaced at alternating intervals of 1200 and 1600 km, for an average spacing of 1400 km. In the course of 7 days the average sample spacing is reduced to 200 km. Since the horizontal resolution of a limb-scanning sensor is no better than about 250 km, this coverage may be considered global even if it does not "paint" the Earth. Sample spacing and refresh times would be smaller toward the poles.

The foregoing remarks apply to a fixed-azimuth limb-scanner: the instrument is equipped with a one-axis scan mechanism which scans the LOS in the elevation direction (up and down across the limb), while the motion of the satellite carries the LOS around the Earth. If required, however, an IRLS can provide dense coverage of the stratosphere by the same means nadir-viewers use to provide dense coverage of the troposphere or surface: by scanning the LOS in azimuth, in a direction perpendicular to the ground track. This is done by adding a two-axis scanning mechanism, so that the sensor can scan horizontally as well as vertically. That is, the sensor can be mounted looking forward on the satellite, execute a vertical scan through the atmosphere, then move the LOS to a new azimuth and execute another vertical scan. It could thus cover a wide swath - 1400 km is enough - just as a nadir-viewer does, and meet the objective requirement of 1-day refresh time for ozone profiles. HIRDLS, which is planned to fly on EOS, is being designed to do this. There would be little point, however, in adding a two-axis scan mode to an MWS: because of the low intensity of the lines it monitors, signal-to-noise ratios would be too small for the additional data points to be useful.

If a fixed-azimuth limb-scanner is used, attention must also be given to its non-equatorial coverage, especially polar. For a single fixed-azimuth limb-scanner, the best overall global coverage, shown in Figure 2 on a one-day basis, is obtained by directing its LOS parallel to the satellite's velocity vector. There is a substantial hole in the coverage around the poles. Better polar coverage, shown in Figure 3, can be obtained with two fixed-azimuth sensors having look directions of ±15° from the velocity vector. The two sensors need not be on the same satellite, a fact that meshes nicely with the desireability of placing them on different satellites for maximum immunity to failure. Figures 2 and 3, which show daily coverage, also indicate why refresh times of 7 days are called for for profile measurements: it takes about that long to obtain a thorough

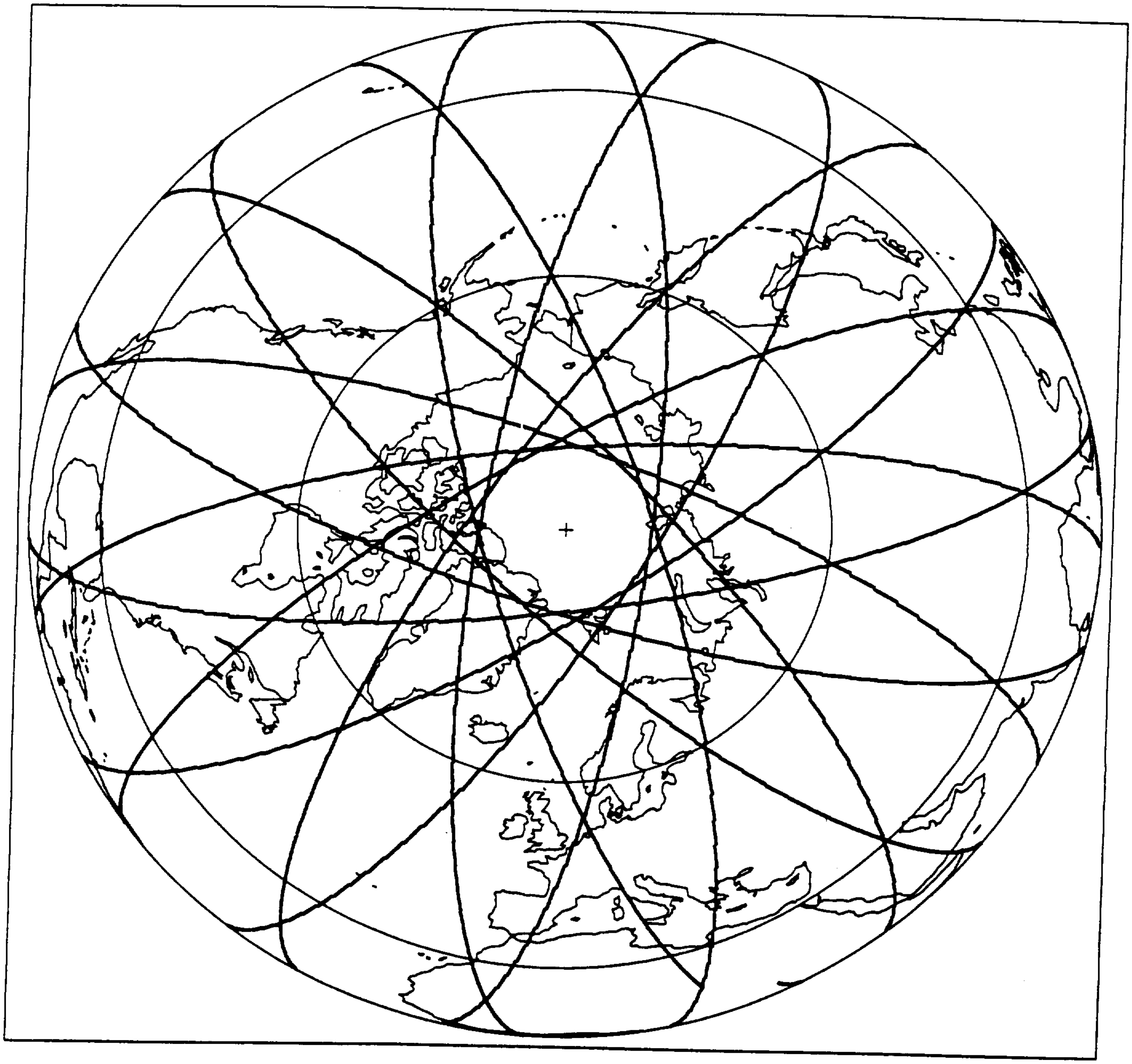
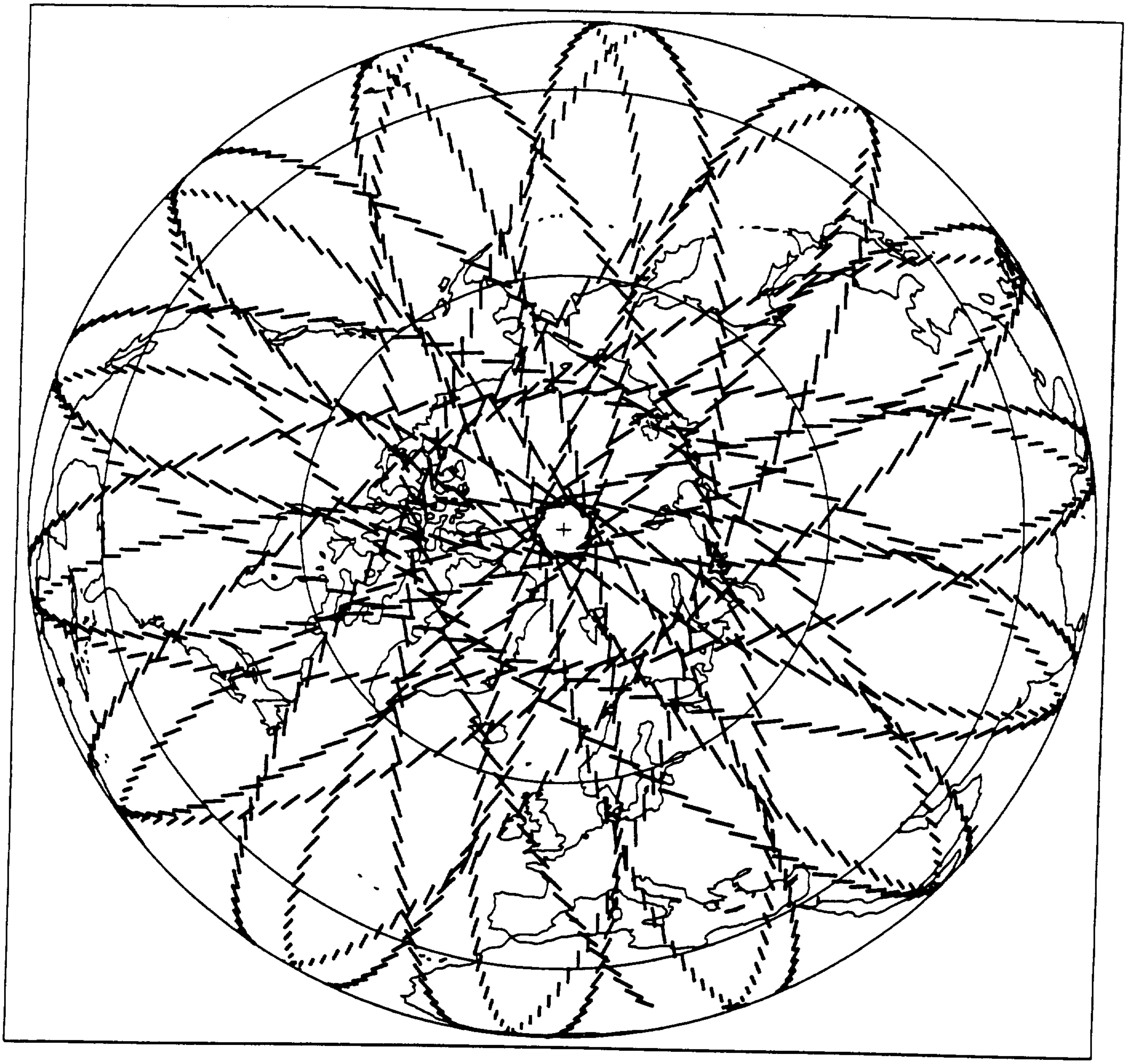


Figure 2. Daily coverage for a single, forward-looking, limb-scanner.



Sun–Synchronous Orbits

Figure 3. Daily coverage for two, 15° side–looking, limb–scanners.

sampling of the stratosphere. A further advantage of the ±15° scheme is that the limb-scanner(s) on the same satellite as the nadir-viewer will be constantly examining a region of the atmosphere that the nadir-viewer will measure about eight minutes later. This will facillitate data comparison.

6b. Solar Occultation Sensors

Figure 4 shows one years' global coverage for an SOS on the 0930 satellite. For the sake of clarity, the observed point in the atmosphere is plotted for only one sunrise and one sunset event per day out of the 14 of each actually observed. As can be seen, observation points occur in a very restricted range of latitudes. On any one day, 14 points at a fixed latitude are obtained; the latitude point then moves slowly north and south during the course of the year. Figure 5 shows the dramatic improvement in gobal coverage for an SOS in a 45° inclined orbit.

7. Background Information on Sensors

7a. Backscatter Ultraviolet Instruments (TOMS/SBUV-type)

The instrument used by NOAA to obtain total ozone and coarse stratospheric ozone profiles is the SBUV-2 (Solar Backscatter UltraViolet spectrometer). This instrument measures backscattered solar radiance in the ultraviolet between 250 and 400 nm, a range that covers the edge of the strong ozone absorption band responsible for protecting the Earth's surface from solar ultraviolet radiation. The measured radiances as a function of wavelength are then inverted to derive the total column density of ozone in the atmosphere, and an ozone profile from about 25 km to 50 km, at an altitude resolution of 7 - 10 km. The field of view of SBUV-2 is 250 by 250 km, with no capability for cross-track scanning. The design of SBUV-2 is based on SBUV, a NASA instrument flown on the Nimbus-7 spacecraft, which operated from 1978 to 1990, and on TOMS (Total Ozone Mapping Spectrometer), a NASA instrument also flown on Nimbus-7, which operated from 1978 to 1993. (A follow-on TOMS instrument was flown on the Russian Meteor-3 spacecraft, but the spacecraft failed in December of 1994.) The TOMS instruments cover a narrower wavelength range (317 to 380 nm). The field of view of TOMS is 50 by 50 km at nadir, with cross-track scanning to obtain complete global coverage in one day. TOMS yields no vertical distribution information: it measures total column density solely and directly.

The SBUV instrument must cover a wide dynamic range of radiance and, to avoid problems from scattered light, uses a double monochromator. The TOMS instrument covers a much smaller dynamic range, and can use a single monochromator. If it is decided to include an ozone limb-scanning instrument (IRLS or MWS) in the payload, then, because of the inherent higher altitude resolution of such an instrument, there would be no need to measure the shortest wavelengths (down to 250 nm) with an SBUV-type instrument in order to obtain coarse vertical resolution. However there is a need to extend the TOMS measurements down to 280 nm, to increase the accuracy of the total ozone measurements at high solar zenith angles. These measurements can still be made with a single monochromator. The inclusion of a simple array detector in the design would increase considerably the capability of the instrument with little or no increase in cost, power, data requirements, or size.

Sun-Synchronous Orbit, 0930 Descending Node

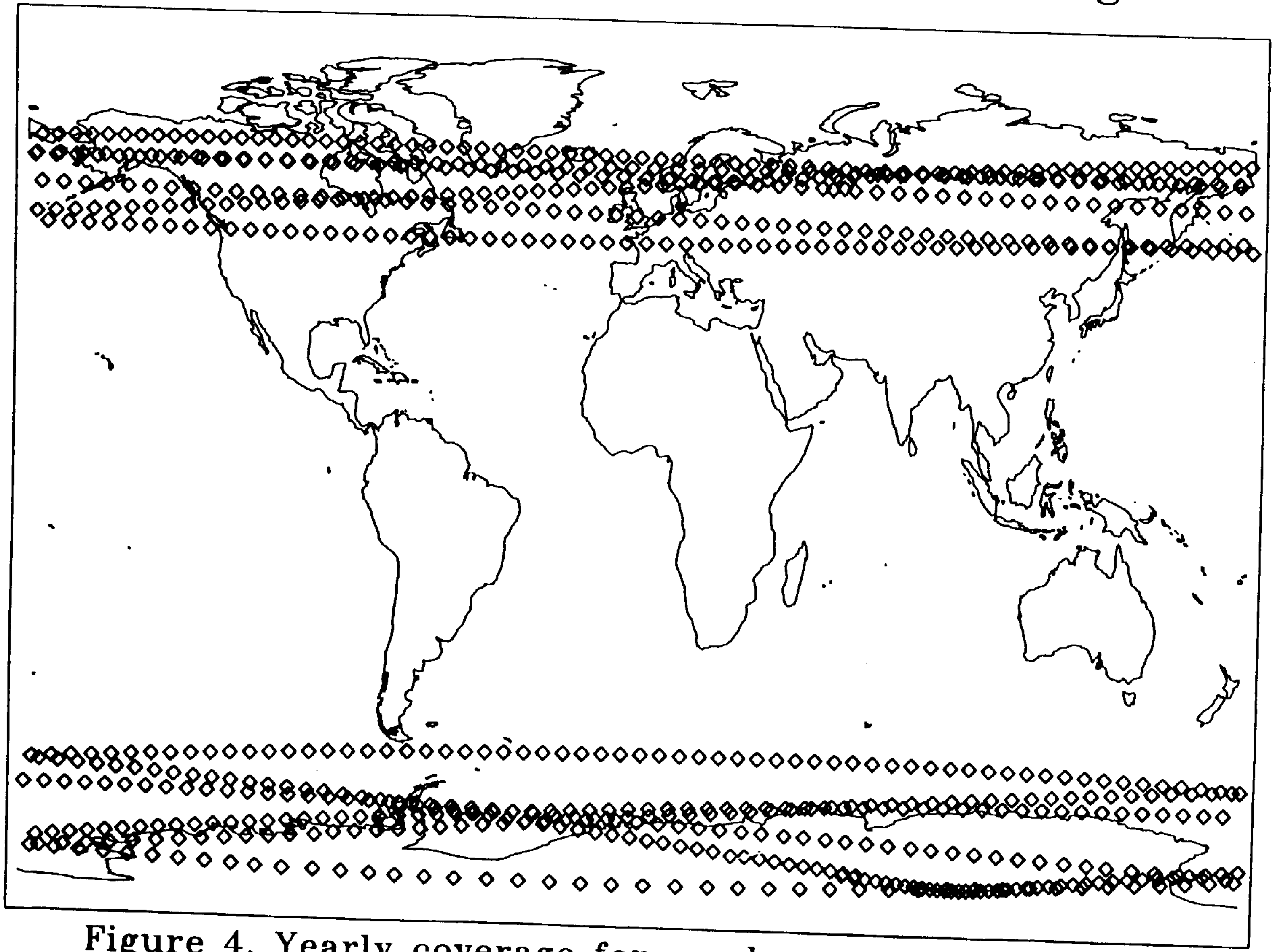


Figure 4. Yearly coverage for a solar occultation sensor, only one event per day plotted.

45° Inclination Orbit

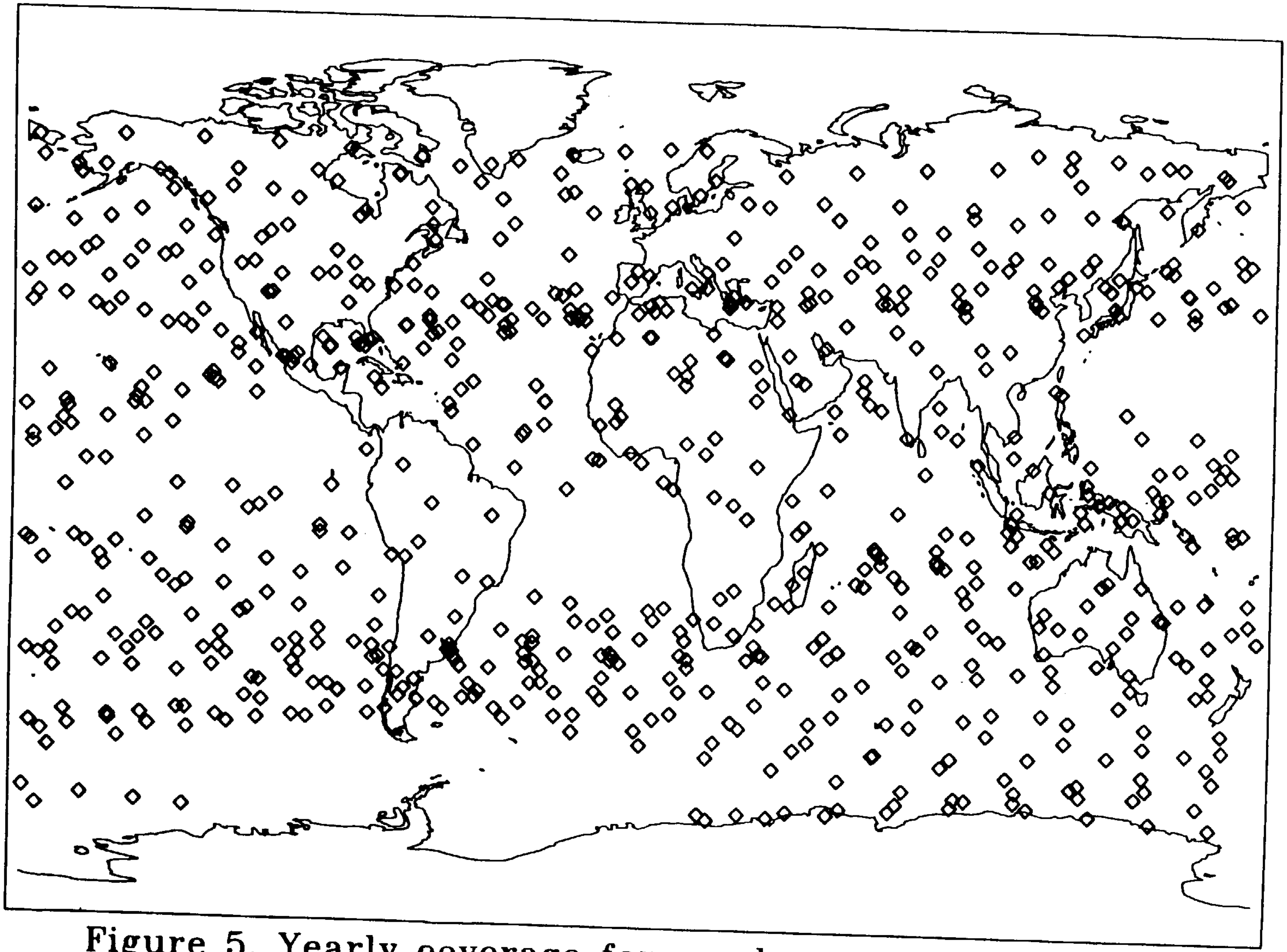


Figure 5. Yearly coverage for a solar occultation sensor, only one event per day plotted.

7b. Millimeter-Wave Spectrometer

Limb-scanning Millimeter-Wave Spectrometers (MWSs) now have a proven record in space: JPL's Millimeter Limb Sounder (MLS) has been operating on the Upper Atmospheric Research Satellite (UARS) since 1991, and NRL's Microwave Atmospheric Sounder (MAS) has flown three times on STS. These two instruments demonstrate the viability of the microwave limb-scanning technique for high-resolution atmospheric sounding of O_3, H_2O, and minor constituents, especially ClO. An MWS detects atmospheric species by their thermal emissions, hence does not rely on sunlight and can provide global day/night coverage. Because of the much longer wavelength of the detected radiation compared to optical/infrared sensors, its measurements are completely unaffected by aerosols: unlike some of the sensors on UARS that were unable to make mesurements when the upper atmosphere was burdened by aerosols from the Mt. Pinatubo eruption, MLS maintained continuous coverage.

MAS, for example, has measured the spatial distribution of H_2O, O_3 , temperature, and pressure in three dimensions with good position and time resolution and has detected ClO and provided some information on its distribution. However, due to the low intensity of the 203 GHz ClO line, many profiles must be averaged to improve the SNR, resulting in very coarse horizontal resolution (thousands of kilometers). Recent advances in space-qualified submillimeterwave RF technology have opened the way to observing at submillimeter frequencies. Better measurements can be made by observing stronger transitions of H_2O, O_3, N_2O and ClO that fall in the 600 GHz range. HNO_3 is also detectable in this region, but still has very weak lines. Consequently, good SNR data require averaging many profiles together, with a concommitant loss of spatial resolution.

The ability to move to the 600 GHz range is important for engineering reasons as well, because it means that, even at the relatively high NPOESS altitude, good vertical resolution can be achieved without the use of an excessively large antenna. Limiting antenna size is important because the antenna assembly must rotate to execute vertical scans of the Earth's limb. The vertical resolution of an MWS with high-quality equipment is given by the formula $R = (\lambda/D)L$, where R is resolution, L is distance from the satellite to the Earth's limb, λ is the wavelength of the radiation, and D is the diameter of the antenna. For the NPOESS satellite altitude of 830 km, $L = 3300$ km. For 600 GHz radiation $\lambda = 0.5$ mm, so choosing $D = 0.6$ m gives $R = 2.8$ km. This is actually somewhat smaller than the 1 m antennas heretofore flown with MAS and MLS. Additional savings in size and weight can be obtained by using an oval-shaped antenna, half as wide as it is tall: 0.6 m × 0.3 m. This can be done because vertical resolution is determined only by vertical antenna height, and the lower horizontal resolution is unimportant in this application.

Another important advance in RF technology that will be of considerable benefit to an MWS for NPOESS is the development of a space-qualified Acousto-Optic Spectrometer (AOS) to replace conventional RF multi-filter banks. An AOS sends the received RF radiation, after heterodyning, into a precision crystal. A laser beam probes the crystal and reads out the RF spectrum. While a well-executed conventional RF multi-filter bank can be fairly light and low-power, a second-generation AOS will be much lighter and need even less power. The first space-borne AOS will fly on the Short-Wave Astronomy Satellite (SWAS) next year, and AOSs will be in an advanced state of development by the time detailed designs for NPOESS will be needed. Another feature that is attractive for the AOS is the inherent high resolution across the entire band. Multi-filter banks achieve their weight performance by having high resolution only in the center of the band, which, at lower frequencies, is usually all that is needed for analyzing the desired line. In the submillimeter portion of the spectrum, however, there is the possibility of very weak lines from other species that can contaminate the spectrum of the desired line. An AOS can measure and correct for this contamination.

7c. Infrared Limb Scanners

The use of limb-scanning IR instruments for measuring ozone profiles has a long history, going back to the Limb Radiance Inversion Radiometer (LRIR) on Nimbus 6 (1975) and the Limb Infrared Monitor of the Stratosphere (LIMS) on Nimbus 7 (1978). More recent examples include the Cryogenic Limb Array Etalon Spectrometer (CLAES) and the Improved Stratospheric and Mesospheric Sounder (ISAMS) on the Upper Atmosphere Research Satellite (UARS). There is also a next-generation instrument, HIRDLS (HIgh Resolution Dynamics Limb Sounder), under development, which is planned to fly on EOS.

These IR instruments can provide profiles of the additional species recommended in Section 4 at relatively minor extra cost, as shown in Table 1. As noted above (Sec. 2c), the retrieval of ozone densities from measurements of thermally-emitted radiation requires that the atmospheric temperature and pressure along the LOS also be measured. Thus, these instruments would provide some level of backup for the primary measurements of temperature and pressure. As has been noted before (Sec. 2c), limb-viewing instruments generally have reduced or no measurement capability for the lower troposphere (typically below 5 to 10 km, depending on the measurement), so they will not be the instrument of choice for obtaining detailed tropospheric information.

While the IR limb-viewing instruments can provide some aerosol information because of the wavelength dependence of aerosol attenuation, this will primarily be at times, if any, of enhanced aerosol loading in the stratosphere. Following Mt. Pinatubo, when the stratospheric aerosol extinction was increased by factors of 100 - 200 in the visible and by 1,000 in the IR, instruments such as CLAES or ISAMS had to correct for aerosol effects. However, for normal stratospheric conditions, solar backscattering or solar occultation measurements will be much more sensitive to aerosol properties.

7d. Solar Occultation Sensors: POAM and SAGE

Solar Occultation Sensors are currently represented on orbit by SAGE II on the Earth Radiation Budget Satellite (ERBS) and POAM II on the French Satellite Pour l'Observation de la Terre (SPOT) 3 spacecraft. SAGE II, a follow-on to the successful Stratospheric Aerosol Measurement (SAM) II experiment on NIMBUS-7, has been operating since 1984; POAM II since November of 1993. Both sensors use the solar occultation technique to measure atmospheric species, as described in Section 5b. POAM II uses the simplest possible hardware: for each of nine separate optical channels, a small (1 cm diameter) lens forms an image of the Sun on a narrow horizontal slit, which subtends an FOV of 0.01°×0.9°. Behind the slit, a spectral filter separates out the waveband of interest and the transmitted light is detected by a silicon photodiode. The optical assembly is mounted on a two-axis, azimuth-elevation gimbal to track the Sun as it rises and sets. POAM II has returned more than 10,000 vertical profiles of ozone and has mapped the formation and dissipation of the Antarctic ozone hole in unprecedented detail.

SAGE II uses a larger collecting area (ten square centimeters instead of POAM's one), a grating spectrometer to separate the desired wavelengths, and a scan mirror to scan its very small FOV (0.008°×0.04°) vertically across the face of the Sun as it rises or sets. The larger optics and grating spectrometer result in higher sensitivity than that achieved by POAM; as previously noted, SAGE II has demonstrated the ability to probe the atmosphere right down to the surface when the LOS is cloud-free. Flying on UARS, which is in a lower-inclined orbit than SPOT (57° instead of 97°), SAGE II has made solar occultation measurements, primarily of stratospheric ozone and aerosols, but often reaching down into the upper troposphere as well, covering all latitudes of the globe except for small regions around the poles.

Improved versions of both sensors (POAM III and SAGE III) are under development.

Acronym List

AOS	Acousto-Optic Spectrometer
CFC	Chlorofluorocarbons
CLAES	Cryogenic Limb Array Etalon Spectrometer
EDR	Environmental Data Record
EOS	Earth Observing System
ERBS	Earth Radiation Budget Satellite
FOR	Field Of Regard
FOV	Field Of View
GCM	General Circulation Model
HCFC	Hydrogenated Chlorofluorocarbons
HSCT	HyperSonic Commercial Transport
HIRDLS	High-Resolution Dynamics Limb Sounder
IORD	Integrated Operational Requirements Document
IR	InfraRed
IRLS	InfraRed Limb-Scanner
ISAMS	Improved Stratospheric and Mesospheric Sounder
JPL	Jet Propulsion Laboratory
LIMS	Limb Infrared Monitor of the Stratosphere
LOS	Line Of Sight
MAS	Millimeter-wave Atmospheric Sounder
MLS	Microwave Limb
MWS	MicroWave (or Millimeter-Wave) Spectrometer
NA	Not Applicable
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRE	Non-Recurring Engineering
NRL	Naval Research Laboratory
OHA	Optical Head Assembly
PCEM	Primary Control Electronics Module
PSC	Polar Stratospheric Cloud
POAM	Polar Ozone and Aerosol
RF	Radio Frequency
SAGE	Stratospheric Aerosol and Gas Experiment
SBUV	Solar Backscatter UltraViolet ozone spectrometer
SNR	Signal-to-Noise Ratio
SOS	Solar Occultation Sensor
SSMI	Special Sensor Microwave Imager
STS	Space Transport System
SWAS	ShortWave Astronomy Satellite
TBD	To Be Determined
TOMS	Total Ozone Mapping Spectrometer
UARS	Upper Atmospheric Research Satellite
UV	UltraViolet