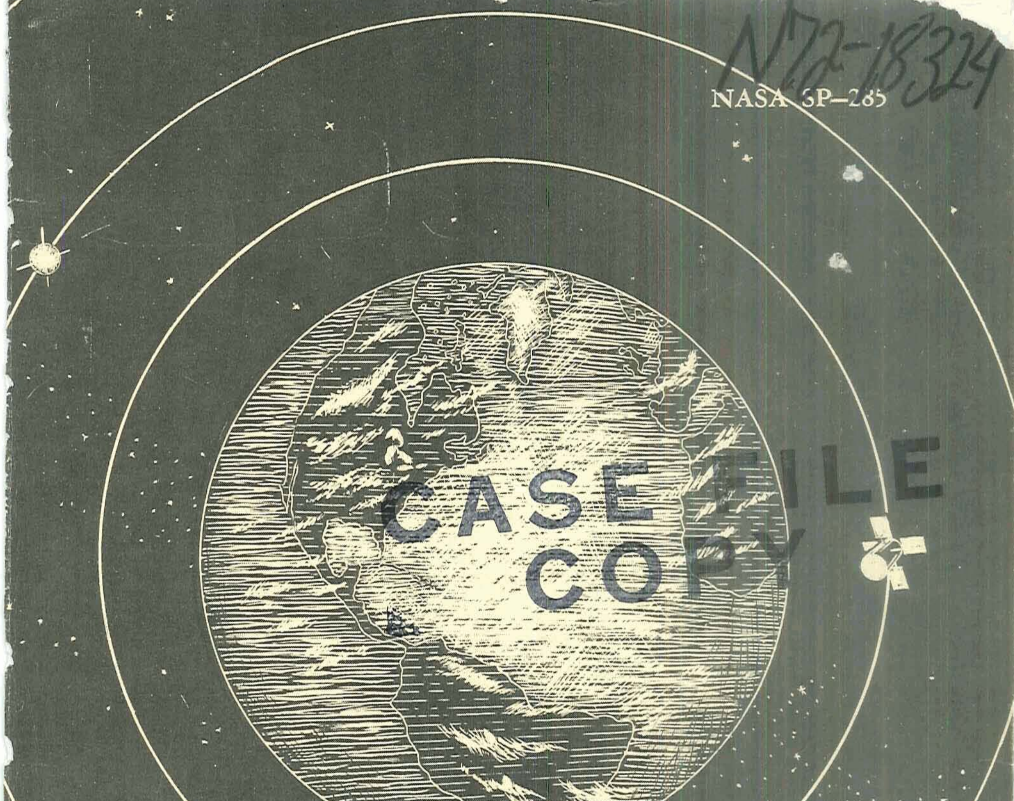
NASA SP-285



REMOTE MEASUREMENT OF POLLUTION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-285

REMOTE MEASUREMENT OF POLLUTION

The report of a working group sponsored by the National Aeronautics and Space Administration, arranged and administered by Langley Research Center, and convened at Norfork, Virginia, August 16–20, 1971

Prepared by NASA Langley Research Center

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PREFACE

Problems of the environment, the assessment of man's influence on his surroundings, and the reciprocal effect of a changed environment on man have been matters of serious concern and active study during recent years. Among the many conferences and symposia on this subject, there have been two milestone conferences held for the purpose of exploring the impact of man on his environment as well as delineating those studies and observational programs that are required for our proper understanding of this man-environment relationship. The conferences identified by their reports are:

1. "Man's Impact on the Global Environment" a report of the Study of Critical Environmental Problems (SCEP) issued by MIT Press in 1970 as a report of a summer study held in Williamstown, Massachusetts, at which about 70 scientists participated.

2. "Inadvertent Climate Modification" a report of the Study of Man's Impact on Climate (SMIC) issued by MIT Press in 1971 as a report of a 3-week study held in July 1971 in Stockholm, Sweden, at which about 30 scientists from fourteen countries participated.

The many recommendations that emerged from these two milestone conferences might be classified into three broad classes:

a. Those that deal with effects of natural or man-created anomalies on weather and climate. In this area, improved numerical simulation models are proposed by means of which we might study the individual effects quantitatively through parametric analysis.

b. Those that deal with increasing our understanding of the physical and chemical processes involved in the many factors underlying changes in our environment. This area involves such subjects as the study of the optical properties of clouds, chemical reactions and rates in the free atmosphere, refraction index of particles, radiative properties of particles, air-sea interaction, etc.

c. Those that deal with identifying and/or monitoring specific contaminants. This class includes gaseous pollutants (e.g., CO_2, NO_x, CO, hydrocarbons, NH_3, ...), particles (e.g., volcanic dust, wind-blown dust, water soluble nuclei, industrial emissions, etc.), and water pollutants (DDT, heavy metals, oil, nutrients, etc.). In each of these, the kinds of data sought are: sources of production, rates of production, routes of distribution, sinks, concentrations, etc.

The primary role of NASA in space applications programs is to develop satellite techniques useful to various activities of man. The development of the meteorological satellite systems for the observation of global weather and of communication satellite systems to augment the capability of ground systems are two dramatic examples of successful space-applications programs.

Thus, it seemed appropriate for NASA to address itself directly to the third class of recommendation listed above—the investigation of the role of remote sensing in identifying and/or monitoring specific contaminants. To that end, a Working Group on Remote Measurement of Pollution was organized and met in Norfolk, Virginia, August 16-20, 1971. NASA's Langley Research Center played a major role in the planning of this conference and made all arrangements for facilities and equipment. The Working Group was divided into five subgroups, which are here listed together with their chairmen:

1. Information on Remote Sensing—H. Reichle, Jr., Chairman
2. Gaseous Air Pollution—W. K. Kellogg, Chairman
3. Water Pollution—G. Ewing, Chairman
4. Particles—V. Suomi, Chairman
5. Instrumentation—G. Manella, Chairman

Langley Research Center participants, working together with the chairmen of the subgroups, prepared a preliminary assessment of the problems of remote measurement of pollution. This document was mailed to participants prior to the meeting, and formed essential background information to the Working Group participants.

The objectives that the Working Group set for itself were to review the important information about pollutants, e.g., their physics, chemistry, biological effects, distributions, etc., and to indicate a consensus of remote sensing possibilities in the identification and monitoring of the pollutants in question. Thus, this report—the output of the meeting—might be considered as an information manual, as of August 1971, which indicates what we know about remote sensing of pollution. The Working Group did not stress the programmatic aspects or systems development possibilities. These, it is felt, could follow logically the issuance of the report of the Working Group and could form the subjects of future discussions.

For easy reference, the major conclusions of this study are presented in a summary which is placed at the beginning of the document. The reader is encouraged to use this summary primarily as a guide and to refer to the body of the document for detailed information in those areas of particular interest to him.

The summary is followed by Section I which presents some basic facts about remote sensing, its advantages and limitations, the spectral characteristics of the clean atmosphere, and the effect of cloudiness. General classes of remote measurement techniques are mentioned as well as platforms for remote sensing. Sections II, III, and IV deal with gaseous, water, and particle pollutions, respectively. In each case, known pollutants are identified, estimates are made of the measurement requirements, and the role of remote sensing is assessed.

Included in the Working Group were about 50 of the leading U. S. authorities in the field of remote sensing of pollution. Thus, it is felt that the report is quite authoritative. In several cases where requirements are stated, the figures given must be considered as best estimates only; however, they are the best estimates of knowledgeable specialists.

In view of the high interest in the results of this review and their potential usefulness for further planning activity, it was decided to issue the report with a minimum of delay. This has required a sacrifice of the additional "scrubbing" time that undoubtedly would have improved the format and readability of the document; however, the consensus of the group was that the information in the report was substantive and useful and should be issued forthwith. The task of organizing this report, editing it, and preparing it for publication was undertaken by Langley Research Center. The material was written by the chairmen with the assistance of the associate and assistant chairmen, in each case, and the over-all editing was performed by Dr. S. Katzoff, also of Langley. The following diagram represents the organization of the Working Group and lists the participants.

WORKING GROUP ON REMOTE MEASUREMENT OF POLLUTION

M. Tepper, Chairman
J. Lehmann, Associate Chairman
H. Reichle, Jr., Associate Chairman
W. Ayers, Assistant Chairman
S. Katzoff, Editor

Basic Information On Remote Sensing	Air Pollution, Gaseous	Air Pollution, Particles	Water Pollution	Instrumentation
W. Ayers	A. Barringer	H. Blau, Jr.	J. Arvesen	J. Arvesen
A. Lefohn	J. Becher	***C. Byvik	**D. Bowker	A. Barringer
G. Mannella	C. Farmer	R. Fraser	G. Clarke	G. Grams
G. Ofelt	J. Gille	G. Grams	D. Delzell	A. Lefohn
A. Park	***G. Grew	T. Haig	S. Duntley	C. Ludwig
*H. Reichle, Jr.	P. Hanst	F. Harris	*G. Ewing	*G. Mannella
A. Sadowski	*W. Kellogg	B. Herman	G. North	P. White
	A. Lefohn	***A. Holland	A. Park	H. Yates
	C. Ludwig	J. Lawrence, Jr.	J. Sherman	
	J. Ludwig	W. Matthews	P. White	
	W. Matthews	**S. Melfi	***W. Witte	
	D. Pack	G. Robinson	J. Zeigler	
	T. Pepin	Z. Sekera		
	**J. Russell, III	*V. Suomi		
	H. Yates			

*Chairman of Panel **Associate Chairman ***Assistant Chairman

NOTE: Affiliations and addresses of the participants are given in the Appendix.

SUMMARY OF THE MAJOR CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

The following is a summary of the major conclusions and recommendations developed by the panels on gaseous air pollution, water pollution, and particulate air pollution during the August 16-20, 1971, meeting of the Working Group on the Remote Measurement of Pollution.

The reports of the Gaseous Air Pollution Panel and the Water Pollution Panel describe specific pollutants and our current ability to measure them by remote techniques.

The report of the Particulate Pollution Panel states that some very important things can be done right away in this area but the full potential requires additional basic research on the scattering and absorption properties of typical aerosol particles.

Thus, it becomes evident from the panel reports that many of the trace gases that concern us are amenable to remote sensing; that certain water pollutants can be measured by remote techniques, but their number is limited; and that a similar approach to the remote measurement of specific particulate pollutants will follow only after our understanding of their physical, chemical, and radiative properties is improved. It is also clear from the reports that remote sensing can provide us with essential information in all three categories that can not be obtained by any other means.

GASEOUS POLLUTANTS AND NATURAL TRACE GASES

IMPORTANCE OF THE PROBLEM

Gaseous air pollutants cause damage to vegetation, irritation to eyes and lungs and other toxic effects, and, possibly, changes in the global climate. The importance of some of these generally invisible gases has been recognized for many years and elaborate techniques have been developed to identify them, to trace them, and to determine their effects. For the most part, however, these techniques have been direct measurement techniques (broadly speaking, techniques that require contact between the gas to be measured and some part of the measuring instrument). Only within the past few years have advances in optical instruments permitted these gases to be traced remotely from the ground, from aircraft and high-flying balloons, and most recently, from satellites. The extraordinary new opportunities for measuring the distributions of these gases that are offered by these new techniques are the subject of this section.

METHODS OF MEASUREMENT

Because satellites (and aircraft to a lesser extent) have the ability to overfly the entire globe, instruments carried aboard these vehicles can obtain an overall picture of a global or regional problem that would be difficult to match by means of measurements taken at scattered points on or near the surface of the earth. On the other hand, because of the limitations imposed by present instruments for the remote measurement of gases in the atmosphere, satellites are usually not appropriate platforms from which to make detailed observations on a local scale. For this reason, we consider only the measurement of those pollutants and trace gases that are important on a global or regional scale. (Regional scale, as used here, signifies areas of one million square kilometers or more.)

In the lower atmosphere, because of the limitations imposed by the present state of the art in the instrumentation field, aircraft and satellite borne remote sensors are better able to determine the *total* burden of gas above a point on the surface than the absolute concentration at some point or the distribution of the gas as a function of height. This may appear to be a severe limitation; however, this capability, which is characteristic of the remote sensing approach, has certain valuable applications. Information on the distribution of total gas burdens over the surface of the earth can be used in conjunction with data on wind velocities and wind structure to quantitatively determine the total amounts of the pollutants present in a given region and to monitor the dissipation of each pollutant and its mass transfer between one region and another. Furthermore, inferences on the vertical structure of pollution can be made when these remotely sensed data are interpreted in conjunction with data from ground-based networks of monitoring stations. It appears therefore that satellite and aircraft monitoring of the lower layers of the atmosphere is in no sense competitive with ground monitoring but is in fact complementary to it, allowing a considerable extension and extrapolation of ground-based data.

In the upper atmospheres, certain techniques (such as limb scanning) that are not usable in the lower atmosphere become available. When these techniques can be utilized it is possible to obtain good height resolution in the measurements.

CONCLUSIONS CONCERNING THE VARIOUS POLLUTANTS AND TRACE GASES

It is clear that one cannot generalize in discussing the various trace gases—both natural contaminants and man-made pollutants—that are of concern to us. Each poses a more or less unique set of problems. It is therefore necessary to treat each constituent separately, first in terms of the kinds of problems and questions that demand an answer, and, second, in terms of our ability to measure its distribution. While we cannot agree on any absolute ranking of the trace gases in terms of the importance of the problems that they present, there is nevertheless a definite sense of urgency in the problems that we will discuss at the outset, either because they relate to the future of the global environment in which we live or because of their pressing scientific interest.

Carbon Dioxide (CO_2)

The atmospheric concentration of carbon dioxide has been increasing since the industrial revolution because of the burning of fossil fuels. This gradual increase has global implications because carbon dioxide traps a part of the infrared radiation that is emitted by the surface, thereby causing an increase in the average surface temperature. While the long term trend in global CO_2 concentration can be adequately monitored by means of a limited number of ground based stations, global measurements of its distribution will prove valuable in tracking the movement of CO_2 from its sources to its sinks. The key to predictions concerning the future levels of CO_2 lies, in part, in the definition of these sources and sinks. It appears that remote techniques using absorption measurements in a downward looking mode with scattered sunlight as the energy source could obtain the required data.

Carbon Monoxide (CO)

This gas is also a product of combustion; furthermore, it is toxic, although toxic concentrations have not been observed in the free atmosphere except in the immediate vicinity of sources. The gas appears to disappear from the atmosphere by means of some as yet unknown mechanism. Studies of its global distribution are thus likely to help in the determination of this mechanism. It appears that the distribution can be determined by remote measurements, either by using thermal emission or by using the absorption of scattered sunlight. Developments utilizing both of these techniques are now under way.

Sulfur Dioxide (SO_2)

By burning sulfur rich coal and oil, man now adds approximately half as much sulfur to the atmosphere as do natural sources. Most of man's contribution is in the form of SO_2 which oxidizes in a few days to form sulfate compounds. Although the average lifetime of the various man-injected sulfur compounds is only a few days, this is sufficient time for them to be carried long distances from their sources. The compounds generally leave the atmosphere through washout by rain, and in the process acidify the rain. This degrades water supplies and causes damage to plants and buildings.

Balloon borne remote sensors using reflected solar ultraviolet light have demonstrated the capability of measuring the total burden of SO_2 in the troposphere. Thus, satellites provide a unique capability to trace the movement of this important pollutant on a continent-wide scale. With further development it is felt that the global distribution of the total burden of SO_2 in the troposphere could also be determined using either thermal emission or reflected solar infrared radiation.

It is particularly important to measure SO_2 in the stratosphere because it leads to the formation of the particle type that is most prevalent there. Two techniques might be applied to determine the SO_2 distribution in the stratosphere. They are both limb-scanning techniques, one using the thermal emission of the gas itself and the second using the absorption of solar radiation by the gas.

Hydrogen Sulfide (H_2S)

This gas is mostly added to the air from natural sources, and it survives about two days before it is oxidized to SO_2 or is removed by rain. At the present time no known remote measurement method is adequate to determine the distribution of this gas.

Ozone (O_3)

Ozone is present throughout the atmosphere. In the lower atmosphere its primary sources are photochemical reactions involving nitrogen dioxide, nitric oxide, and hydrocarbons; in the stratosphere its primary source is a natural process involving the interaction of solar ultraviolet radiation and molecular oxygen. The stratospheric ozone layer filters out the ultraviolet radiation at wavelengths between 0.2 μm and 0.3 μm from the solar beam. Since radiation at these wavelengths is harmful to most of the life forms that exist on the surface of the earth, the continued existence of the ozone layer is of extreme importance. The complex photochemical processes that determine the ozone content of the upper atmosphere involve many other trace substances including water vapor and nitric oxide. These processes are not well understood. Because of the possibility that high flying aircraft might upset the natural balance in this region, it is important that a good inventory of ozone and the compounds with which it interacts be obtained.

Remote measurements of the total burden of ozone in the atmosphere to an accuracy of approximately 5% have been demonstrated by instruments aboard the Nimbus III and

IV satellites. Measurements of the vertical distribution of ozone in the high stratosphere and mesosphere have been obtained by limb scanning absorption techniques that use a star as a radiation source. Total stratospheric ozone measurements using backscattered solar ultraviolet energy have been demonstrated aboard the Nimbus IV satellite. An experiment for determining the vertical distribution of stratospheric ozone using the visible radiation of the sun has been demonstrated aboard a balloon and is under development for the OSO-J satellite, and a technique to obtain the same data by means of thermal infrared measurements is under development for flight aboard Nimbus F.

Stratospheric Water Vapor (H_2O)

Stratospheric H_2O has been mysteriously changing in the past decade, possibly due to volcanic activity, but that is still far from certain. Since the effect of supersonic aircraft operation on water vapor concentration in the stratosphere is still uncertain, and since it may be significant, it is exceedingly important that we understand the water vapor distribution and the processes that control it. Two methods of remotely measuring stratospheric water vapor distributions have been demonstrated in rocket flights. The first of these scanned the earth's limb using thermal emission. Further development of the method will be required to achieve the required measurement accuracy. The second method used solar infrared radiation in a limb transmission mode. This technique has the potential of making measurements into the mesosphere.

Nitrogen Compounds (NO, NO_2, HNO_3, NH_3, N_2O)

The nitrogen compounds are produced naturally; NO and NO_2 are also produced in the combustion of fossil fuels. Ammonia (NH_3) is produced by industrial processes. Although their concentrations are generally small and their toxicity relatively low, they play very important roles in the photochemical processes that govern the production of such secondary pollutants as ozone, the PAN's, etc., which are indeed damaging. These oxides of nitrogen could be added to the stratosphere by jet aircraft in sufficient quantities to alter the ozone distribution, although the magnitude of this effect is still a matter of considerable uncertainty. In any case, the distribution of these ubiquitous and active oxides of nitrogen in both the troposphere and stratosphere should be better known and should be monitored.

Measurements of the total NO_2 in the troposphere using reflected solar visible radiation, and measurements of stratospheric HNO_3 using thermal emission from or solar transmission through the limb, have been demonstrated aboard high altitude balloons. Measurements of total tropospheric NO, using vertical measurements and thermal emission, and of total tropospheric NH_3 using vertical measurement and reflected sunlight are thought to be possible at the present time if suitable types of instrumentation are applied. Measurements of NO_2, NO, N_2O, and NH_3 profiles in the stratosphere are thought to be possible at the present time if currently available instrument techniques are applied to the problem. The technique would use limb scanning in the visible or infrared depending upon the particular gas to be measured.

Halogens and Their Hydrides (Cl_2, Br_2, I_2, HCl, HBr, HI, HF)

The halogens are all volatile and exist in the air as gases, as do their hydrides. The hydrides are released as pollutants from the burning of trash and from certain industrial activities. They are harmful even in small concentrations, especially HF. The concentrations of these gases just above the sea surface may also be an indication of the bio-productivity in the water. Iodine in the air, it has been suggested, can combine with lead or other substances to produce freezing nuclei that can influence precipitation.

The measurement of total iodine, using reflected visible sunlight, has been demonstrated during an aircraft flight. The measurement of total HCl and total HF in the troposphere, using reflected solar infrared radiation, is thought to be possible.

Fluorocarbons

Volatile fluorocarbons, of which freon is perhaps the best known, are released in vast quantities into the atmosphere and must remain there as virtually permanent components of the atmosphere—at least we know of no removal mechanisms. The question naturally arises as to whether this continual release will create a problem as they continue to build up. No remote methods for the measurement of these compounds could be identified.

Methane (CH_4)

Although very considerable quantities of CH_4 are released into the atmosphere by the tapping of natural gas, the mining of coal, and the processing of petroleum, it seems likely that most of the very appreciable quantity of CH_4 in the atmosphere is produced in natural processes, mostly biological. This gas does not play a major role in the heat balance of the atmosphere, but it may account for half of the water vapor that we find in the upper atmosphere above about 40 km. It is possible that it might be measured in the stratosphere by limb scanning techniques using thermal or solar infrared radiation.

Other Hydrocarbons ($\langle HC \rangle$)

The hydrocarbons that are released into the atmosphere by man constitute an important part of the "photochemical brew" that we recognize as smog, and virtually all of the damaging or toxic gases produced in polluted air (except the sulfates) are derived from hydrocarbon reactions. Measurement of these compounds in the stratosphere may become possible with further instrumentation development.

Mercury (Hg)

This trace metal that has received so much attention as poison in several parts of our food chain is somewhat volatile, and the atmosphere undoubtedly serves as one route from its source—usually manmade—to its sinks, generally water bodies. It would be helpful in controlling its spread to be able to trace it through the atmosphere. No remote method for measuring the distribution of this pollutant could be identified.

MEASUREMENT REQUIREMENTS

Tables 1 and 2 list the various gases, the associated problems, and the measurement accuracies considered to be necessary in order to study their distributions adequately by remote sensing techniques. Table 1 includes gases that have a recognized environmental impact; Table 2 includes those for which concern is of a speculative or long-term nature. Problems of global concern are placed in one grouping and those affecting only particular regions of the globe are included in a second grouping. (Regional problems were considered to be those having a scale of about 10^6 square kilometers.) Local problems were not identified in this study.

MEASUREMENT CAPABILITIES

Table 3 summarizes findings of the Gaseous Air Pollution Panel concerning present measurement capabilities. Column 1 lists the gases that were considered. Column 2 indicates the height range of the measurements, which was restricted in this study to levels between the stratopause (about 50 km) and the surface. The third column is a tabulation of the vertical resolution capability provided by a given measurement approach. The entry "Total" indicates that the measurement approach gives the integrated amount of gas between the ground and the instrument. Column 4 gives a rating of the ability of the measurement approach to provide the required accuracy as specified in Tables 1 and 2. Column 5 indicates the measurement approach according to the following code:

I. Limb Measurements
   1. Thermal emission
   2. Limb absorption

TABLE 1

REQUIREMENTS FOR MEASURING POLLUTANTS WITH A RECOGNIZED ENVIRONMENTAL IMPACT

<table>
<tr><th colspan="3">GLOBAL</th></tr>
<tr><th>Constituent And Region Of The Atmosphere</th><th>PROBLEM: Why are we concerned?</th><th>Accuracy</th></tr>
<tr><td>CO_2</td><td>Measure its increase, which is a factor in climate change</td><td>0.5 ppm</td></tr>
<tr><td>SO_2 - Upper Troposphere And Stratosphere</td><td>Formation of particles in the stratosphere from SO_2 carried upward from the troposphere or injected by volcanos and SST's</td><td>0.5 ppb</td></tr>
<tr><td>O_3 Stratosphere</td><td>What causes the long term changes in distribution of ozone? Is there a correlation with solar activity?</td><td>Total Content 1%
Distribution With Height 10%</td></tr>
<tr><td>H_2O Stratosphere</td><td>(a) Determine effect on ozone concentration
(b) Determine effect on radiation balance of stratosphere
(c) Determine influence on particle size distribution in the sulfate layer</td><td>Total Content 20% for (a)
Much less accuracy for (b)
Distribution With Height 0.5 ppm for (c)</td></tr>
<tr><td>NO_x Stratosphere</td><td>Determine effect on ozone concentration</td><td>NO_2 and NO 10 ppb</td></tr>
<tr><th colspan="3">REGIONAL</th></tr>
<tr><th>Constituent In Lower Layers</th><th>PROBLEM: Why are we concerned?</th><th>Accuracy</th></tr>
<tr><td>SO_2</td><td>(a) Damage to plants
(b) Particle formation which subsequently contributes to acid rain</td><td>10 ppb</td></tr>
<tr><td>H_2S</td><td>(a) Oxidizes to SO_2
(b) Its natural source is uncertain</td><td>0.1 ppb (?)</td></tr>
<tr><td>NO_x</td><td>(a) Damage to plants and toxicity at PPM concentrations
(b) Photo-oxidation of hydrocarbons and particle formation
(c) Precursor of PAN's</td><td>0.1 ppm for (a), 10 ppb for (b) and (c)</td></tr>
<tr><td>$\langle HC \rangle$</td><td>(a) Lead to particle formation by photochemical processes
(b) Lead to noxious and toxic products</td><td>$\langle$ 1 ppb (?) (necessary to distinguish species)</td></tr>
<tr><td>O_3</td><td>Irritant and destructive; a product of photochemical processes involving $\langle HC \rangle$ and NO_x</td><td>10 ppb</td></tr>
<tr><td>PAN's</td><td>A class of toxic and irritant products of photochemical processes</td><td>1 - 10 ppb</td></tr>
<tr><td>Hg</td><td>Atmosphere transports Hg, which is toxic where it accumulates in the biosphere</td><td>10^{-2} ppb</td></tr>
<tr><td>Heat Released</td><td>A factor in regional climate change</td><td>—</td></tr>
</table>

Note: This table is the same as Table I of Section II.

TABLE 2
REQUIREMENTS FOR MEASURING POLLUTANTS FOR WHICH CONCERN IS SPECULATIVE OR LONG TERM

GLOBAL		
Constituent And Region Of The Atmosphere	PROBLEM: Why are we concerned?	Accuracy
CO Troposphere And Stratosphere	(a) Is concentration changing due to man's burning of fossil fuels? (b) Determination of destruction processes in the stratosphere	10 ppb
HNO_3 Stratosphere	(a) Determine effect on ozone concentration (b) Does it influence aerosol formation?	1 ppb
⟨HC⟩ Stratosphere	Do they influence aerosol formation?	Not determined except for CH_4. ⟨HC⟩ have not been detected in the stratosphere
CH_4 Troposphere And Stratosphere	(a) Participates in photochemical reactions in the lower atmosphere (b) What is its influence on stratospheric H_2O (and O_3) distribution	Troposphere 0.5 ppm Stratosphere 0.2 ppm
Fluorocarbons Total	(a) Probably accumulating due to man's releases	$<$ .001 ppb (?)
N_2O Stratosphere	Determine its rate of photodissociation in the stratosphere	50 ppb
REGIONAL		
Constituent In Lower Layers	PROBLEM: Why are we concerned?	Accuracy
CO	(a) Determination of sources, sinks, and lifetime in lower atmosphere (b) Participates in photochemical reactions (c) Indicative of oceanic processes	10 ppb
H_2CO	(a) Participates in photochemical reactions (b) Irritant at concentration near 1 PPM	1 ppb
Halogens	(a) Toxic and damaging (especially fluorine and HF) (b) Bromine is indicative of bioproductivity of the oceans	1 ppb
NH_3	Combines with sulfuric acid to form $(NH_4)_2SO_4$ particles	10 ppb

Note: This table is the same as Table II of Section II.

TABLE 3

MEASUREMENT CAPABILITIES FOR REMOTE SENSING OF TRACE GASES

Constituent	Altitude Range Of Measurement	Altitude Resolution	Capability	Measurement Approach
CO_2	Entire	Total	Potentially Feasible	II.2 - SOLAR IR. Required accuracy will be very difficult to obtain.
$(C^{13}O_2/C^{12}O_2)$	Entire	Total	Feasible	II.2 - SOLAR IR. Not required measurement, but may be useful in distinguishing between sources.
CO	Troposphere	Total	Feasible	II.1 and II.2 - SOLAR IR and THERMAL IR
SO_2	Troposphere	Total	Demonstrated In Tests-Regional Potentially Feasible-Global	II.2 - SOLAR UV. Demonstrated from a balloon, using a correlation spectrometer
			Feasible-Regional Potentially Feasible-Global	II.1 - THERMAL IR
			Feasible-Regional Potentially Feasible-Global	II.2 - SOLAR IR
	Stratosphere	FEW km	Potentially Feasible	I.2 - SOLAR IR and THERMAL IR
		FEW km	Potentially Feasible	I.1 - THERMAL IR
O_3	Stratosphere	2 km	Feasible	I.1 - THERMAL IR. Under development for NIMBUS F.
		0.5 km	Demonstrated In Tests	I.2 - SOLAR visible. Demonstrated on balloon. Under development for OSO-J.
		Total	Demonstrated In Tests	II.2 - SOLAR UV. Flown on Nimbus 4. Accuracy of $<10\%$ achieved. Method can also give height distribution above O_3 maximum
	High Stratosphere And Mesosphere	1 km (?)	Demonstrated In Tests	I.2 - STELLAR UV. Results have been obtained, using OAO data, for altitude range - 60 km to 100 km.
	Entire	Total	Demonstrated In Tests	II.1 - THERMAL IR. Flown on Nimbus 3 and 4. Accuracy - 5% achieved.
H_2O	Troposphere	?	Demonstrated In Tests	II.1 - THERMAL IR. Flown on Nimbus 3 and 4. Does not meet accuracy requirement; measurement in high troposphere difficult.
	Stratosphere	2.5 km	Demonstrated In Tests	I.1 - THERMAL IR. Flown on a rocket but required accuracy not achieved.
		1 km	Demonstrated In Tests	I.2 - SOLAR IR. Flown on a rocket. Potentially can extend to mesosphere.

Note: This table is the same as Table III of Section II.

TABLE 3 (continued)

MEASUREMENT CAPABILITIES FOR REMOTE SENSING OF TRACE GASES

Constituent	Altitude Range Of Measurement	Altitude Resolution	Capability	Measurement Approach
NO_2	Troposphere	Total	Demonstrated In Tests	II.2 - SOLAR visible. Demonstrated on a balloon, using a correlation spectrometer
			Feasible	I.2 and II.2 - SOLAR IR and THERMAL IR.
	Stratosphere	FEW km	Feasible	I.2 - SOLAR VISIBLE
			Potentially Feasible	I.1 - THERMAL IR
NO	Troposphere	Total	Feasible	II.1 - THERMAL IR
	Stratosphere	FEW km	Feasible	I.2 - THERMAL IR
<HC>	Stratosphere	FEW km	Potentially Feasible	I.1 or I.2 - If concentrations are in PPB range
CH_4	Stratosphere	FEW km	Feasible	I.1 or I.2 - THERMAL IR or SOLAR IR
H_2CO	Troposphere	Total	Potentially Feasible	II.2 - SOLAR IR and SOLAR UV. Capable of measurements in PPB range but required accuracy not known.
C_2H_2	Troposphere	Total	Potentially Feasible	II.2 - SOLAR IR. Capable of measurements in PPB range but required accuracy not known.
C_2H_4	Troposphere	Total	Potentially Feasible	II.2 - SOLAR IR. Capable of measurements in PPB range but required accuracy not known.
H_2S	Troposphere	?	Not Currently Feasible	?
N_2O	Stratosphere	FEW km	Feasible	I.1 or I.2 - SOLAR IR or THERMAL IR
I_2	Troposphere	Total	Demonstrated In Tests	II.2 - SOLAR visible. Demonstrated from an aircraft over marine source
HCl	Troposphere	Total	Feasible	II.2 - SOLAR IR
HF	Troposphere	Total	Feasible	II.2 - SOLAR IR
HNO_3	Stratosphere	FEW km	Demonstrated In Tests	I.1 or I.2 - THERMAL IR or SOLAR IR. Demonstrated in balloon experiment.
NH_3	Troposphere	Total	Feasible	II.2 - SOLAR IR
	Stratosphere	FEW km	Feasible	I.1 or I.2 - THERMAL IR or SOLAR IR.
Fluorocarbons	Troposphere	Total	Not Currently Feasible	
Hg	Troposphere	?	Not Currently Feasible	?
Heat Released	Surface	Total		Depends upon ability to measure surface temperature, air temperature change, wind, water vapor, etc., since heat released will take many forms.

- II. Vertical measurements
  1. Thermal emission
  2. Absorption techniques

From the foregoing discussions of the possibilities for measuring the various pollutants an overall conclusion is clear: The era of remote measurements of the distribution of many of the trace gases that are of concern to us is here.

RECOMMENDATIONS OF THE PANEL ON GASEOUS AIR POLLUTION

1. The distribution of those gases in the stratosphere that play a part in determining the ozone photochemistry and radiative equilibrium be measured concurrently on a global basis from satellites. The primary constituents of interest are O_3 itself, H_2O, NO, NO_2, HNO_3, and CH_4. It is not established that all of these gases can be measured with current techniques; therefore a development program should be undertaken to establish the feasibility of measuring these distributions to the required accuracy.
2. Remote measurement techniques from satellites be exploited to measure regional and global distributions of gaseous pollutants in the troposphere, the objective being to establish sources and sinks and to assess the roles of these gases in the environment. Those trace gases that may be measured in this manner to the required accuracy are CO, SO_2, NO_2, NO, and possibly CO_2.
3. Studies be initiated to establish relationships between vertical burden and surface concentrations of trace gases and the results be used in the planning of complementary programs to measure pollutants from the ground and space.
4. Remote measurement techniques be developed and applied to determine vertical concentration profiles of pollutants, and these measurements be used to improve dynamic transport models and to study space and time variations.
5. Research programs be conducted to establish accurate values of the basic absorption properties of pollutant molecules (that is, line strengths, half-widths, and positions) in the infrared and microwave regions of the electromagnetic spectrum.

6. Emphasis be placed on the use of aircraft and balloon platforms in addition to satellites for studying regional pollution problems and in evaluating techniques for eventual use on satellites.
7. Research programs be encouraged to further advance the state of the art beyond the current instrumentation capabilities given in Table 3, with particular emphasis on those systems which appear to be potentially feasible.
8. Studies be initiated to assess the potential of microwave techniques for remotely sensing gaseous pollutants.
9. Research programs be established to study the potential of active systems employing lasers for use in remote sensing of gaseous pollutants.

REMOTE MEASUREMENT OF WATER POLLUTANTS

IMPORTANCE OF THE PROBLEM

Water pollution has become a problem of great importance in large areas of the world. It occurs world wide, in bodies of water as diverse as the farm pond and the open ocean. The present situation has come about primarily as a result of both man's rapid population growth and his rising standard of living. Because uncontrolled water pollution threatens both man's water supply and his food supply it is necessary that systems to rapidly detect and measure water pollution be developed.

METHODS OF MEASUREMENT

Because of the particular spectral characteristics of water itself (it is reasonably transparent to electromagnetic radiation *only in a rather narrow spectral region centered at 0.5 μm)* and the characteristics of the pollutants (most of them do not display the sharply defined spectral signatures that are characteristic of gases, for example), the number of pollutants that can be directly detected in water by remote means is rather limited.

The methods available for remote monitoring of water pollution fall into three broad categories: *in-situ* sensors coupled to telemetry; direct detection by sensors aboard a satellite; and inferential methods based on observation of material not in itself classed as a pollutant.

In-situ Methods

Reference here is to fixed or floating stations using sensors in direct contact with the pollutant. Conventional methods of assay are available for this application, but they will in most cases have to be modified for continuous unattended use. The techniques for interrogating and relaying acquired data via satellite are presently operational and rapidly being improved. The limitations on this approach are imposed by high operating cost, collecting and processing large volumes of data, vulnerability to tampering, loss of data through storms and other casualties, and lack of representativeness of spot data over meaningful areas.

Direct Sensing

Where available, direct sensing will undoubtedly be the preferred method. Pollutants detectable from space include major oil spills and large-scale thermal emissions. Disturbances of beaches and estuaries and other effects of man's cultural activities are likewise observable directly. The chief limitations on direct methods include lack of specificity (as of oil, for example) and the optical inertness of many pollutants such as lead and biocide sprays.

Inferential

Since, in the last analysis, pollution is usually harmful because of some biological effect, either directly on man or on the usefulness and habitability of his environment, reaction of the biota is a powerful, if indirect, way of monitoring pollution. Fortunately, because life is a surface phenomenon in the global sense, usually existing exposed to sunlight and air, the biota contains a large assortment of sensitive and observable plants, animals, and living communities which indicate the health or sickness of the total environment. A further inherent advantage is that the sentinel biota integrates effects of pollution over time regardless of whether damage occurs continuously or intermittently.

CONCLUSIONS CONCERNING THE VARIOUS POLLUTANTS

As in the case of the remote measurement of gaseous pollutants it is not possible to generalize and include all pollutants in one measuring system. The following eight categories of pollutants were selected as being susceptible to measurement by remote sensing techniques.

Oil Pollution

Now that huge quantities of crude oil and petroleum products are transported in ships, the problem of oil pollution of both surface waters and benthic communities has increased considerably. In addition, offshore drilling of oil wells has produced important local pollution problems. These are certain to increase in importance as the Atlantic Coastal area is opened to exploration for oil deposits. The nature and extent of pollutant oil must be quickly determined if proper corrective actions are to be started.

Because oil is less dense than water it initially floats on the surface. ("Initially" because certain fractions are dissolved from crude oil by water and the residue eventually sinks.) The presence of an oil deposit on the water causes a change in the surface viscosity of the water and alters the capillary wave structure. This produces a change of the apparent emissivity of the water in the microwave region and hence a change in brightness temperature. It therefore appears that microwave radiometry is capable of detecting this smoothing of the ripples by the oil film. Further, at near normal incidence angles oil is highly reflecting in the ultraviolet region while water is highly absorbing. It appears then that microwave radiometry is best suited to the initial detection of oil spills. It would be effective in either day or night and in the presence of some clouds. The use of multifrequency radiometers would allow some determination of film thickness. As the film disperses and thins the use of particular spectral regions (the ultraviolet or visible, for example) may allow one to follow the variation of film thickness.

Suspended Sediment

Because of the spread of cities and the concomitant building and soil disturbances, more and more shifting of soil into water basins and drainage systems is occurring. This is causing extensive disturbance to fresh water streams and lakes and to the estuarine and salt water marsh habitats. This sediment acts in several ways to cause problems. When suspended it reduces water clarity and sunlight penetration, thereby affecting the biota. As it settles to the bottom it buries and kills vegetation and alters the benthic biota. It also fills channels and harbors, requiring expensive remedial measures.

Turbid water is clearly visible from satellite altitudes. Mapping of ocean water clarity has been shown feasible by studying the 70 mm color transparencies taken during Gemini flights. It has also been found that there is a correlation between turbidity and the apparent reflectance of vertically polarized light, as had been predicted by theory. Since the measurement of 1% polarization has been shown to be within the capability of existing digital photometric mappers, this technique holds great promise for the quantitative measurement of water turbidity.

Chemical and Toxic Wastes

Since he began to manufacture and, in the process, produced unwanted byproducts, man has dumped them into the nearest stream. Typically, they have been dumped without treatment, and sometimes considerable effort has been expended to hide the dumping from public view, e.g., outfalls are placed on river bottoms, or dumping is carried out at night. A second and increasingly important source of chemical and toxic wastes is the widespread use of biocides. These are now used worldwide for the control of plant and insect pests. Many of them degrade only very slowly and are concentrated in the food chain.

Although it may not be possible to detect specific pollutants in these effluent streams, it may be possible to detect the presence of the effluent through some of its characteristics. The spectral properties of the effluent may be different from those of the receiving water, or the effluent may be at a different temperature and thereby subject to thermal detection. Finally the presence of the toxic material may be inferred through the destruction or anomalously low concentration of some indicator species. Remote sensing using thermal mappers or multispectral scanners appears to be an excellent tool for monitoring this type of pollution. Precise identification of the specific pollutant will probably require follow-up ground surveys of the remotely detected effluent.

Solid Wastes

Man has not been a tidy animal with respect to his own biological waste products. As long as populations were low and dispersed, nature's recycling systems were able to accommodate such material. Recent population growth and concentration have caused these natural systems to be overwhelmed. Recent changes in agricultural practices (the shift to cattle feed lots and mass poultry production for example) have greatly aggravated the situation by introducing large amounts of waste from these operations into the groundwater and streams. Monitoring of sewage outfalls is limited to a few point measurements (and many people are not served by sewers). Remote sensing offers many advantages and could make a significant contribution in this area. False-color infrared film possesses great potential here. The algae blooms that can usually be found in the enriched waters can easily be seen with this film. Multispectral scanners may also have application to these problems. Required ground resolution is high (of the order of ten meters, although one hundred meters would be useful in many problems) but could probably be achieved.

Thermal Effluents

Water has been used extensively as a coolant in both manufacturing processes and power generation. The heated water is discharged into the original source, often causing a temperature rise of from 2° to 10° C. Temperature elevations of this magnitude exceed the temperature tolerances of many species of animals and plants. Chemical reactions are accelerated and the solubility of important gases (such as oxygen in water) is considerably reduced. With the expected increase in number of nuclear power plants, greater quantities of heated water will pour into drainage systems, lakes, and even the oceans.

The measurement of water surface temperature has been performed from both aircraft and satellites by means of remote infrared sensors. Measurements of the temperature and position of large ocean currents (the Gulf Stream and the Kuroshio) have been made with instruments aboard the Nimbus and ITOS satellites while numerous measurements of smaller features have been obtained using aircraft-borne instruments.

Radioactive Wastes

The escape of naturally occurring radioactivity into the environment is not significant; however, with the rapidly expanding use of nuclear power generation it is expected that the radioactive material introduced into the water by man may become a much more widespread environmental problem. It now appears that certain longlived isotopes are concentrated as they move up the food chain. Their ultimate effect is unknown.

At the present time airborne gamma ray counters can be used to detect regions of anomalously high radioactivity, and they have been used for this purpose. No known methods are now available for the remote sensing of surface radioactivity from satellites.

Nutrient Wastes

In addition to the solid wastes mentioned earlier, sources of nutrient wastes are agricultural fertilizer runoff, detergents, and industrial wastes.

The remote detection of these pollutants usually cannot be carried out directly. Measurements of chlorophyll will, however, generally indicate the presence of enrichment. The comments on instruments under the section entitled Solid Waste apply here also.

Living Organisms

Through changes like the damming of rivers, the building of canals between formerly unconnected bodies of water, or the building of harbors, man often upsets the existing ecological balance, which leads to explosive growth in some populations and the destruction of others. At other times man either intentionally or inadvertently introduces new species to a body of water by means of overland transport. In any case, one would like to know of the changing relationships among the species and of the spreading of undesirable species at an early stage.

Remote sensing can prove very useful here. Because of the large areas over which these problems occur, ground based sampling systems are either inadequate or prohibitively expensive. Generally, film cameras and multispectral scanners should have application here.

INSTRUMENTATION FOR REMOTE SENSING OF WATER POLLUTION

The sensing of specific local instances of water pollution has been accomplished for many years from aircraft and/or boats through visual identification of the source and documentation of the scene on film by means of a camera. The last several years have seen a rapid evolution of instrumentation having high potential for regional and global pollution monitoring. The instrumentation includes: (1) imaging scanners, capable of providing a view of the scene outside the spectral range of the human eye or any film emulsion, (2) imaging spectrometers, capable of rapid, detailed spectral analysis of the radiation (solar or thermal) leaving a water body, (3) correlation instruments, such as the Fraunhofer Line Discriminator or the Chlorophyll Correlation Radiometer, which are capable of eliminating the background signal through prior knowledge of unique spectral characteristics of the pollutant or its manifestation, (4) microwave radiometers and radar, which are capable of providing all-weather, day/night capability of detecting oil spills, (5) pulsed laser systems, which are potentially capable of remote, detailed analysis of individual pollutants through excitation and detection of their fluorescence characteristics, and (6) specialized instruments, such as low light level imagers and scintillation detectors which are capable of sensing bioluminescence and radioactivity.

These instruments can be used at various levels of a multistage sampling program whose components are satellite observations, detailed aircraft surveys, and *in-situ* monitoring and analysis stations.

Table 4 lists the measurement requirements for the remote sensing of each category of water pollution discussed previously. A dual-entry system is used in the table to designate the optimum value and the acceptable value of each measurement requirement when applicable.

Table 5 lists 14 different types of instruments used in remote sensing and shows the correspondence of these instruments to each of the categories of water pollution discussed previously.

As can be seen from the foregoing, there are several important problems in the area of water pollution to which remote measurement can be applied. Because much of the measurement must be done in the visible and near infrared portions of the spectrum it is likely that the technology developed for the remote sensing of land surfaces can be applied.

RECOMMENDATIONS OF THE PANEL ON WATER POLLUTION

1. This Panel recommends an acceleration of research related to the application of remote sensing techniques to the special problem of water pollution. Applicable biological disciplines should be given an important role in this work.
2. We believe that an assemblage composed of *in-situ* fixed or drifting stations, aircraft, balloons, and satellites will provide the most economical and effective overall method for the detection and quantitative monitoring of water pollution. In this multiplex system, the function of spacecraft should be dominant.

TABLE 4

MEASUREMENT REQUIREMENTS FOR REMOTE SENSING OF POLLUTION

An optimum value and an (acceptable value) are given for each entry.

N/A—not applicable

	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	SPECTRAL RANGE	TEMPORAL RESOLUTION	SOLAR ELEVATION	LOOK ANGLE (FROM NADIR)	AREA COVERAGE
Oil	10-30m (300m)	Broad-band	Ultraviolet, Visible, Microwave	2-4 hrs. (1 day)	Only important with glitter	Only important with glitter	200x200km (20x20km)
Suspended Sediment	20m (500m)	.15μ m (.15μ m)	350-800nm (400-700nm)	2 hrs. (1 day)	45° (30°-60°)	0 to +15° (−5°to+30°)	350x100km (10x10km)
Chem. & Toxic Wastes	10m (200m)	.015μ m (.015μ m)	350-700nm (400-700nm)	5 hrs. (10 days)	45° (30°-60°)	0 to +15° (−5°to30°)	35x35km (10x10km)
Solid Wastes	10m (200m)	.015μ m (.015μ m)	350-800nm (400-700nm)	5 hrs. (10 days)	45° (30°-60°)	0 to +15° (−5°to+30°)	35x35km (10x10km)
Thermal Effluents	30m (500m)	±0.2°C (±1°C)	10-12μ m (10-14μ m)	2 hrs. (10 days)	N/A	To be determined	35x35km (10x10km)
Radioactive Wastes	30m (500m)	N/A	gamma (gamma)	5 hrs. (15 days)	N/A	0° (o°)	35x35km (10x10km)
Nutrient Wastes	100m (2km)	.005μ m (.015μ m)	400-700nm (400-700nm)	2 days (14 days)	45° (30°-60°)	0 to +15° (0 to +30°)	350x350km (35x35km)
Intro. of Species	To be determined	.1μ m (.1μ m)	Visible (Visible)	3 mos. (yr.	N/A	N/A	350x350km (10x10km)
Red Tide	30m (2km)	.015μ m (.015μ m)	400-700nm (400-700nm)	5 hrs. (2 days)	45° (30°-60°)	0 to 15° (−5° to +30°)	350x350km (20x100km)
Human & Cultural Effects	10m (100m)	Variable	Ultraviolet, Visible, Microwave	1 yr. (5 yrs.)	N/A	N/A	350x350km (35x35km)

Note: This table is the same as Table IV of Section III.

MEASUREMENT REQUIREMENTS FOR REMOTE SENSING OF POLLUTION

TABLE 5

SENSOR/APPLICATION CORRESPONDENCE FOR REMOTE SENSING OF POLLUTION

1—PRESENTLY AVAILABLE
2—UNDER DEVELOPMENT
3—POTENTIAL APPLICATION

*—WITH INFRARED CHANNEL

		FILM CAMERAS													
		U/V	COLOR	COLOR I/R	MULTISPECTRAL	MULTICHANNEL SCANNING RADIOMETER	CORRELATION RADIOMETER	FRAUNHOFER LINE DISCRIMINATOR	PULSED LASER SYSTEM	LOW LIGHT LEVEL DEVICES	I/R IMAGER-SCANNER	MICROWAVE RADIOMETER	RADAR	SCINTILLATION DETECTOR	POLARIMETER
OIL		1	2	3	1	1	1	1	1		2	1	1		1
SUSPENDED SEDIMENT			1	1	1	1	2		2						2
CHEM. & TOXIC WASTES			2	3	2	2	2	3	2						
SOLID WASTES			1	1	1	1	2		2						2
THERMAL EFFLUENTS						1*					1	1			
RADIOACTIVE WASTES														1	
NUTRIENT WASTES			1		1	1	1		2						3
LIVING ORGANISMS	INTRO. OF SPECIES		2		2	2				3					
	BACTERIA								3						
	RED TIDE		1	1	1	1	1		1						
	HUMAN & CUL. EFF.		1	1	1	1				1	1		1		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14

Note: This table is the same as Table V of Section III.

3. Because of the complex interrelations of the natural world, this Panel recommends that the particular problems arising from pollution be studied in the context of the total environment in which they are embedded.
4. The systems evolved should and can be multipurpose, adapted to the needs of agricultural, atmospheric, and oceanic users. Such commonality must, however, be real and mutual, with no special use allowed to degrade the effectiveness of the system for some other use.
5. In order to provide for an orderly and rapid advance in this field, NASA should now design and implement a Prototype Operational Environmental Monitoring System. Such a prototype system would extend at least over the entire United States and nearby ocean and should be intimately responsive to the needs of regional activities and adapted to the solution of special problems that exist in particular areas of the country.

PARTICLES IN THE ATMOSPHERE

IMPORTANCE OF THE PROBLEM

Atmospheric particulate matter has important climatic, biological, and economic effects that range from local to global in scale. It is responsible for the costly soiling of materials, buildings, and textiles, and is an important factor in accelerating the corrosion of steel and zinc. Biologically, high concentrations of particles can lead to an increase in respiratory illnesses and in the death rate in man and animals. The particulate matter may stunt plant growth, interfere with pollination, make plants more susceptible to pathogens, and, if the dust contains a soluble toxicant, may directly damage plants.

The presence of an increased number of hygroscopic sulfate and nitrate particles leads to increased acidification of precipitation. The acidity of precipitation affects the soil, forests, and bodies of water. There are indications that the acidity of precipitation in the Northeastern United States is increasing. Particles affect the transfer of radiation through the atmosphere by their ability to absorb, emit, and scatter radiation. In the visible portion of the spectrum, the scattering of radiation by particles can equal or exceed the scattering due to the normal gaseous constituents. In some cities the long-term average of solar radiation reaching the ground is reduced by particles by more than 10%.

The interactions of aerosols with solar radiation may change the global albedo. The direction, increase or decrease, of a possible albedo change depends upon the optical properties of the particles, and of the underlying surface. Any change of global albedo must lead to a change in the mean temperature of the planet earth; that is, to a change in the climate. Thus, there is a growing concern to monitor the earth's albedo.

DIFFICULTIES OF MEASUREMENT

The true role of particles in the transfer of radiation through the atmosphere is difficult to assess because of a lack of knowledge of their optical properties and of their spatial and temporal distribution. In principle, we seek to infer the structure of an unknown medium by examining the radiation scattered or emitted by the medium as a function of the direction of the incident radiation, its intensity, polarization, and wave length. In general, classical transfer theory allows us to predict the energy transmitted or reflected by a plane-parallel medium under plane-wave illumination for several special cases, one of which is a medium free of particulate matter. It is easy enough to see the difference between clean and dirty air; it is another thing to say what the dirty atmosphere is carrying. The difficulties inherent in the transfer problem for more general cases are such that a considerable theoretical and experimental effort will be needed to resolve them. There are two distinct stumbling blocks. The first obstacle is a virtually complete lack of knowledge of the detailed scattering and absorption properties of typical aerosol particles; that is, nonspherical or irregular particles possibly coated with liquid or ice and having diverse chemical compositions. We have practically no information on how such particles scatter electromagnetic energy and how these properties change with scattering angle, with the wavelength and polarization of the incident energy, and with the complex refractive index of the particles with respect to the surrounding medium. Table 6 summarizes present day capabilities in dealing with problems of radiation transfer through an atmosphere that contains particles as well as normal molecular constituents.

MAN-MADE VERSUS NATURAL CONTRIBUTIONS

To determine the effect of man's contribution a distinction should be made between natural particulate matter and that which is man-made. The atmosphere contains a background level of particulate matter which plays an important part in the radiation budget of the earth-atmosphere system. Man-made contributions, superimposed on the natural background, may alter this budget and cause a change in climate on a local or, possibly, a global scale. Assessment of the effects of the man-made (pollutant) portion is much more difficult than may appear at first glance. There is little doubt that over many populated areas atmospheric turbidity is increasing. Solar radiation measurements in Japan and in the European part of the USSR show this increase clearly. However, very few long-time records of atmospheric turbidity are available from regions far enough removed from local sources of pollution to give a representative picture of global turbidity. One such record, from Mauna Loa Observatory, Hawaii, dates back to 1957. Analysis of these data up to 1967 indicates a long-term increase in turbidity. A later analysis of these data through 1970 showed that the Mauna Loa turbidity has recovered nearly to its 1957 level and that, on a global scale, it is probable that natural aerosols are the prime contributor to global atmospheric turbidity. Best current estimates are that man-made particles comprise 5-10% of the global particle loading, although the literature contains a much wider range of values.

Clearly, it is important that a world-wide monitoring system be established as soon as possible so that future changes may be recognized promptly. Remote sensing may provide the basis for this system.

TABLE 6

PRESENT DAY CAPABILITIES IN DEALING WITH PROBLEMS OF RADIATIVE TRANSFER THROUGH AN ATMOSPHERE THAT CONTAINS PARTICLES

Key:
Yes—The quantity can be computed.
No—The quantity can not be computed.

Model	Emergent Fluxes	Internal Flux Divergence	Intensity and Polarization Distribution	Heating Rates (λ integration)	Inversion
1. Plane-parallel, horizontally homogeneous atmosphere, with homogeneous boundaries					
a. Vertically homogeneous	Yes	Yes	Yes	Yes	No
b. Vertically inhomogeneous	Yes*	Yes*	Yes*	Yes*	No
2. Plane-parallel horizontally inhomogeneous atmosphere	No	No	No	No	No
3. Spherical atmosphere	Yes**	Yes**	Yes**	Yes**	No

Note: This table is the same as Table I of Section IV.

*While this is soluble with currently available methods, it is felt that more work is needed on these solutions in order to make them more expedient.

**These problems are soluble in principle, but the solutions for them have not, at this time, been published.

RECOMMENDATIONS OF THE PANEL ON PARTICLE POLLUTION

A Coordinated Research Program

1. We recommend initiation of a coordinated physio-optical research program whose purpose will be to advance our level of understanding of the optical properties and behavior of the real atmosphere. We feel strongly that the most effective way to achieve this purpose is to identify a center devoted to that purpose. If none can be identified, such a center should be organized.

Earth's Radiation Budget

2. *Global Albedo.* We recommend immediate attention to the task of measuring the earth's albedo and its long-term variability. We advise the use of flux sensors detecting the ratio of outgoing to incoming solar radiation simultaneously on satellites in different orbits. An accuracy of 1 percent or better is required.

Investigation is required of:

(a) The instrumental problems, including initial standardization and intercomparison in orbit.

(b) The sampling problem—what groupings of available orbital types give suitable earth coverage?

(c) The organizational problem presented by a single experimental project of long duration requiring space on several different types of satellites.

(d) The possibilities of international cooperation.

3. *Terrestrial Radiation.* We recommend monitoring of the outgoing flux of terrestrial radiation with the same global coverage and long-term stability as the albedo measurement.

Monitoring Atmospheric Particles

Satellite-Borne Methods

4. We recommend that consideration be given to broadening the geographical coverage of an experiment like that

planned for the OSO-J stratospheric particle experiment to include measurements of distributions at higher latitudes. This will provide, quickly and economically, basic data for evaluating the stratospheric aerosol problem.

5. We recommend study of the use of a photopolarimeter in a geostationary satellite. We also recommend use of a cooled infrared spectrometer from a near-earth orbit for study of more dilute distributions than can be sensed with photometers and to furnish information on the chemistry of the particles.

6. We recommend monitoring the atmospheric turbidity on a global scale by measuring the polarization of upwelling radiation with fast-response photopolarimeters, from particular target areas, keeping the area in the field of view during a satellite traverse in order to obtain information for a range of angles.

7. We recommend determination of stratospheric turbidity by studying the intensity and polarization gradients across the terminator as measured from satellites by existing photometers, modified to measure the polarization.

8. We recommend development of satellite-based lasers for monitoring the spatial distribution of stratospheric and tropospheric aerosols on a global basis.

Monitoring Atmospheric Particles—Ground-Based Methods

9. We recommend that a world-wide network of atmospheric turbidity monitoring sites be established in order to determine what changes, if any, in world-wide turbidity are occurring, or will occur in the future, due to man-made particulate matter. More specifically, we recommend monitoring by laser radar of the particle content of the lower stratosphere by both ground-based and airborne systems.

10. For determining low-level turbidity near pollution sources we recommend a net of observing stations equipped with:

(i) Fully automatic photopolarimeters to measure the degree of polarization of the skylight and the positions of the neutral points.

(ii) Instruments to measure the diffuse intensity gradient in the solar aureole.

11. For determining the secular trends in atmospheric turbidity, we recommend ground-based skylight polarization measurements in locations of low turbidity (mountain tops, arctic and/or antarctic regions).

Supporting Studies

12. We recommend study of how the scattering matrix elements of real aerosol particles differ from those of spherical particles; and how they change with wavelength, particle size, refractive index, size distribution, and shape. These measurements can be made with randomly oriented particles, using polar nephelometers.

13. Concurrent efforts should be applied to developing mathematical models of the scattering properties of nonspherical randomly oriented particles. Such models should be tested against the measured properties and improved. We must also develop improved models of the transfer of electromagnetic energy in the real atmosphere, including the following:

(i) Develop more refined computational models for the plane-parallel, horizontally homogeneous atmospheres (models 1(a) and 1(b) in Table 6) in order to provide more accurate results requiring less computational time. Also, results from existing techniques should be cross-checked against one another to provide some insight into their relative accuracy.

(ii) Research should be inaugurated to incorporate spherical geometry into these models, either by modifying existing models or through developing new techniques.

(iii) Research should be inaugurated to develop models capable of handling horizontal inhomogeneities.

(iv) Current models should be employed to infer the consequences of increasing levels of atmospheric turbidity, using known or suspected chemical compositions of man-made and natural aerosols.

SECTION I

BASIC FACTS CONCERNING REMOTE SENSING

W. Ayers
A. Lefohn
G. Mannella
G. Ofelt
A. Park
*H. Reichle
A. Sadowski

*Chairman of Panel

SECTION I

BASIC FACTS CONCERNING REMOTE SENSING

GENERAL CONCEPTS, ADVANTAGES, LIMITATIONS

BASIC APPROACH

Before proceeding into the specifics of the remote measurement of pollutants it may be useful to discuss the general concepts of remote sensing, the advantages and disadvantages thereof, and the instruments and platforms by means of which remote measurements can be made. Most of the non-remote measurement techniques now in use are derived from analytical methods that were developed in laboratories where controlled environments could be developed and maintained. When it becomes necessary to perform the measurements outside the laboratory situation (in nature as it exists) it is often found that these laboratory type measurements become difficult or even impossible to perform. This may be caused, for example, by the inaccessibility of the region to be measured or by the changes in the measured property that are induced by the mere presence of the measuring instrument. In this situation remote measurements may be of significant advantage. Further, for certain classes of problems having to do with large-scale phenomena, such as pollution measurement or, more generally, environmental monitoring on a regional or global basis, aircraft- and satellite-borne remote sensors appear advantageous because of the large geographical coverage that they afford.

Many materials selectively absorb, transmit, reflect, and emit electromagnetic radiation. With the present state of the art of electro-optical instrumentation, it is possible to accurately record the radiated and reflected portions of this energy at considerable distances from their source. Remote sensing then utilizes this recorded information to infer the properties of the emitting or reflecting medium. It includes many different sensing devices, varying from the classic photographic camera to complex multi-frequency active and passive microwave instrumentation.

Remote sensing research has followed a specific logic which has led to the present state of the art and which will undoubtedly continue; namely,

(i) Identify the specific chemical, physical, or biological properties of the material or of the environmental parameter to be measured that affect the absorption, transmission, reflection, or emission of electromagnetic energy.

(ii) Identify those wavelengths in the electromagnetic spectrum that yield interpretable information when the quantity to be measured is viewed from the appropriate platform.

(iii) Identify the instrumentation parameters, e.g., calibration sensitivity and signal-to-noise ratio, that are required to make the measurement.

ADVANTAGES OF REMOTE SENSING FROM MOBILE PLATFORMS

Remote sensing of a quantity has a number of advantages. Among these are:

(i) The state of the medium is minimally changed in the process of making the measurement. (This is particularly true of the so-called passive techniques in which one senses the naturally occurring radiation that is leaving the system under study.)

(ii) The instrument can sample remote areas on a regular basis.

(iii) The same instrument is used to make the measurements at all places. This third advantage of global satellite sensing can hardly be overemphasized. Information traditionally obtained by point measurements from instruments located at widely spaced geographic locations can be obtained by synoptic viewing with a single instrument. The remote measurement technique provides a set of internally consistent data, and the instrument calibration problem is reduced to the problem of calibrating a single instrument. With periodic verification of sensor performance this means that it is possible to remove not only static instrument errors but also, in many cases, dynamic errors. Such periodic verification may require daily or weekly in-flight calibration over specially instrumented test sites on the surface, but the importance of homogeneous data far outweighs the problems and the bother involved in calibration.

The value of this approach is exemplified in a recent test application of the University of Michigan airborne multispectral optical mechanical scanning radiometer in an agricultural crop inventory program. In every possible case extensive correlating surface measurements and surface observations of the remotely scanned area were made. In spite of the care taken in the collection and collation of the surface data there were many cases of disagreement between the remotely sensed record and the surface records. In most of the cases (>90 percent) the error was found to be in the record (map) made on the ground. Most of the surface errors were traced to the lack of adequate sampling (not enough area) or simple human error in making the record. Even though the remotely sensed record presented many problems to the interpreter, e.g., sun angle effects, look angle effects, detector responsivity, and tape recorder fidelity, it had two great virtues—complete objectivity and complete coverage of the scene.

LIMITATIONS OF REMOTE SENSING

At the present time it appears that satellite remote sensing platforms could provide bases from which to observe synoptic over-all effects including specific air pollutant identification, total pollutant vertical burden (ppm-m), upper atmosphere horizontal burden, secondary effects of water pollution (stimulated algae growth), air and water plumes, thermal surface anomalies, land use characterization, and particulate scattering (qualitatively). However, the problems of quantitatively measuring water pollutants at a particular point, ground level air pollution concentration, or vertical profiles of air pollution are not now amenable to solution by remote measurement techniques from satellite platforms. The first two of these are still best handled by conventional direct methods of measurement. The third, that of obtaining vertical profiles of air pollution , is not now amenable to solution by remote measurement techniques; it may eventually be handled by active remote probing using tunable lasers. At the present time, however, the large weight and power requirements of the laser techniques make them not feasible for satellite use until an economical large payload capability (i.e., space shuttle) is developed.

Besides providing a testing pad for future satellite experiments, aircraft-borne remote sensors provide data similar to that of satellite-borne sensors (with the exception that aircraft-borne sensors generally scan through a larger angular range, which somewhat complicates data interpretation) and at the present time are subject to similar limitations. Of course, the geographical coverage of the measurements is limited by the altitude and range capabilities of the particular aircraft. Aircraft-borne instruments can, however, provide measurements of very high spatial resolution.

TRANSMISSION THROUGH THE CLEAN ATMOSPHERE

OVERVIEW

Use of remote sensing techniques requires that the spectral properties of the clean atmosphere be known. These techniques, whether active or passive, involve the interpretation of some pattern of electromagnetic radiation that has been emitted by a source of known characteristics and that has been modified in its passage through the atmosphere. The modifications to the beam that occur during its passage through the atmosphere will depend strongly on the composition of the atmosphere in the path and less strongly on the distribution of pressure and temperature along the path. As an example, the infrared ($> 5\mu$ m) absorption spectrum of the entire atmosphere as seen from a satellite will differ markedly from the infrared absorption spectrum of the atmosphere below an aircraft flying at an altitude of 15 kilometers. In the latter case the absorption bands of ozone and nitrous oxide would be much weaker since these gases exist primarily in the stratosphere and mesosphere. By examining the spectral characteristics of the clean atmosphere through which the measuring instrument will look one can find regions of reduced absorption or "windows" to be used by passive remote sensing techniques, or one can determine permissible wavelengths for the active studies. Since, in general, there are no spectral regions in the atmosphere that are perfectly transparent, the information sought concerning the pollutant will appear in the form of deviations from the spectral characteristics of the clean atmosphere.

Figure 1 shows a low resolution transmission spectrum for a vertical path through the entire atmosphere. It can be seen that there is a large amount of structure in this spectrum. (Actually, this spectrum is very highly smoothed; the true spectrum has two to three orders of magnitude more structure than is shown here.)

In the remainder of this section the spectral properties of the clean atmosphere are discussed in somewhat greater detail. For convenience, the entire spectrum is divided into regions (following the generally used nomenclature) and each region is discussed separately beginning with the shorter wavelengths and proceeding to the longer wavelengths. The effect of clouds is discussed separately at the end of the section.

THE ULTRAVIOLET REGION, $\lambda < 0.4\ \mu$m

The transmission of the entire atmosphere is very nearly zero for wavelengths below 0.3 μm (Fig. 1). The transmission then increases rapidly with increasing wavelength, and is very nearly 1.0 throughout the visible region. The primary absorbing constituents in the ultraviolet region are molecular oxygen and ozone. Most of the absorption occurs in the stratosphere (where the ozone is concentrated) and above. The molecular-oxygen bands primarily involved are the Schumann-Runge continuum and the Schumann-Runge bands between 0.1 and 0.2 μm and the Hertzberg continuum between 0.2 and 0.24 μm. The absorption by ozone occurs primarily in the Hartley region and Huggins bands between 0.15 and 0.35 μm. Because of the strong absorption by these bands, relatively little energy from the sun reaches the ground at these wavelengths, so that passive measurements using reflected sunlight are difficult. Because the ozone is concentrated in the stratosphere it does not interfere to any

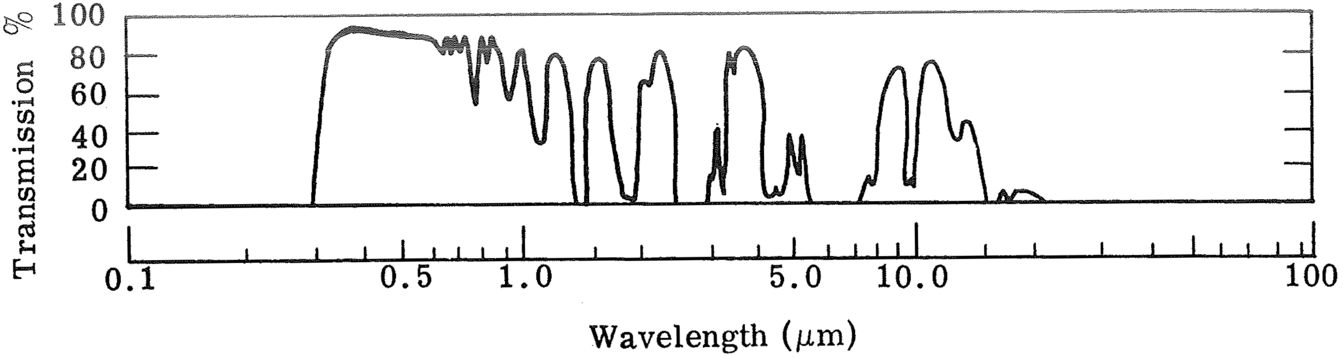

Figure 1.- Transmissivity of the Clear Earth Atmosphere (vertical path).
(After Frisken, 1971)

great extent with active measurements made at these wavelengths in the lower atmosphere. Capabilities of these techniques in the lower atmosphere are enhanced by the presence of the ozone, since the measurements are always made under essentially "nighttime" conditions, with the attendant increased signal-to-noise ratios.

THE VISIBLE REGION, 0.4 μm $<\lambda<$ 0.8 μm

In this region the atmosphere transmits approximately ninety percent of the incident solar radiation. This fact, coupled with the fact that the solar spectrum peaks in this region, causes approximately one half of the total solar energy received at the surface of the earth to be received in this spectral interval. There are a few weak atmospheric absorption bands in this region, particularly toward the longer wavelength end. These are caused primarily by ozone, molecular oxygen, and water vapor. The ozone band of importance is the Chappuis band centered at 0.6 μm. Molecular oxygen has bands centered at 0.6379, 0.6884 and 0.7621 μm, while water vapor has several bands between 0.5437 μm and 0.8465 μm. All are relatively weak bands. Also of importance in the visible (and the ultraviolet) are the effects of molecular and aerosol scattering. The effects of molecular scattering can be handled quite well by means of Rayleigh scattering theory. The scattering caused by the larger aerosol particles can (in principle) be handled by Mie theory; however, the calculation is much more difficult.

THE INFRARED REGION, 0.8 μm $<\lambda<$ 100 μm

In this region there are many overlapping abosrption bands. The major infrared-active gases are water vapor, ozone, carbon dioxide, and nitrous oxide. Water vapor is concentrated in the troposphere (approximately the first 14 km of the atmosphere) and its concentration is highly variable in both space and time. Carbon dioxide is nearly (to within a few percent) uniformly distributed over the globe to an altitude of approximately 100 km. At the present time its mixing ratio is approximately 320 ppm and is increasing at a rate of approximately 0.7 ppm per year. Nitrous oxide, like ozone, is found in the stratosphere and above. As can be seen from the foregoing, the most important infrared-active gases are trace constituents in the atmosphere. The major constituents (nitrogen and oxygen) are essentially transparent at these frequencies. (Their presence does, however, affect the absorption of radiation by the trace gases.) If one is operating in the troposphere using the earth as a source (At wavelengths longer than approximately 3.5 μm, the thermal emission of the earth itself is a stronger source than is the solar energy reflected by the earth. At shorter wavelengths, the opposite is true.) the effects of ozone and nitrous oxide are minimized; however, absorption by water vapor is ubiquitous and one must correct for its effects at all wavelengths. The net effect of the various trace gases is that over the entire spectral range from 0.8 to 100 μm only a few relatively narrow regions (so called window regions) are available for remote measurements. The two most important of these are the 8-12 μm region and the 4.6-4.8 μm region.

THE FAR INFRARED AND MICROWAVE REGION, $\lambda > 100\ \mu$m

The atmosphere is nearly transparent in much of this spectral region. However, because of low detector sensitivity, the far infrared is not now very important for remote sensing purposes and the major effort has been in the microwave region. Water vapor has rather strong absorption lines at 0.926 mm, 0.928 mm, 1.64 mm, and 13.48 mm with a number of weak lines elsewhere. Molecular oxygen has a single absorption line at a wavelength of 2.5 mm and an absorption band at a wavelength of 5 mm.

THE EFFECTS OF CLOUDS

If clouds are in the path of the radiation, the energy at infrared wavelengths and shorter is both scattered and absorbed by the water droplets. Since approximately 50% of the globe is cloud-covered at any time, this imposes a serious constraint on remote measurement systems if the properties of the surface or of the troposphere are to be measured. Because most of the clouds exist in the troposphere they do not impose a serious constraint on measurements of the properties of the stratosphere. Certain microwave regions of the spectrum are essentially unaffected by the presence of clouds, so that measurements can be made through them at these wavelengths. If measurements of tropospheric or surface properties must be made at infrared wavelengths or shorter, the spatial resolution must be high enough to allow viewing through the clear areas between clouds. Of course, one must also know when clouds partially fill the field of view. This is generally determined by means of an independent observation.

REMOTE MEASUREMENT TECHNIQUES

CLASSES OF TECHNIQUES

The instruments that are used in remote sensing can be grouped into a few general categories. These various categories of instruments are discussed here. Specific instruments and their application to particular problems are discussed in the later sections of this report. Remote measurements of pollutants can be generally grouped into three classes:

1. Those that identify a given species or confirm its existence in the atmosphere or the oceans;
2. Those that measure the total amount of a pollutant over a given area, i.e., the total burden;
3. Those that measure the distribution of pollutant along some axis such as the vertical or a line-of-sight.

Not only the information provided but also the complexity of the required instrumentation and data reduction are very different for these three classes. (All increase in the order in which the classes are listed.) Hence continuing trade-off studies are required to determine the type of measurement that can and should be made.

A majority, but not all, remote measurement techniques are dependent upon the use of electromagnetic radiation in some fashion. Acoustical probing, for example, is a remote sensing technique that does not use electromagnetic radiation. However, only methods that use electromagnetic radiation are discussed in this report (except for those methods that use *in-situ* measurements, with telemetry of their information). One may differentiate between active and passive systems. Early measurement techniques tended to sense available energy emitted by or reflected from the medium being sensed; such techniques are termed passive. Photography by natural light is probably the best known example of such techniques. Passive techniques are generally simpler and less expensive than active techniques, but are also less versatile. The best known active sensing technique is radar, which was invented about 30 years ago and has come into widespread use in many remote sensing applications today. Experimental systems using lasers instead of microwave tubes have successfully been developed in the past decade. Active systems enjoy the advantage of being able to influence the magnitude of the returned signal by controlling the output of the transmitter, and are hence less restricted by limitations of the naturally available energy. They are, however, more complex and require more power than passive systems.

Remote sensors can be further categorized according to their prime characteristics. Following is a description of some of the more important general classes of remote measurement instruments.

CAMERAS

As the simplest form of imaging system, cameras have been used with considerable effectiveness as remote sensors in aircraft and satellite platforms. Even in their simplest forms, such as metric cameras and multispectral cameras imaging on film, these instruments can be utilized both in manned systems and in unmanned systems employing film recovery techniques. These instruments have several advantages—for example, providing a permanent data record which can yield absolute values when the system is appropriately calibrated. They suffer from limited magazine storage capacity, the latent nature of the image, and nonlinearities in response, which make weak sources difficult to record properly.

Electronic scanning techniques can also be employed to provide an image output. Television cameras and vidicon tubes have been used in spacecraft to return images of the earth and also images of remote areas such as lunar and planetary surfaces. Multispectral television cameras have been proposed for sensing vegetation vigor and ocean pollutants. These systems enjoy the advantage of virtually unlimited imaging capacity provided that communication channels of sufficient data rate are available for transmission of the digitized data to the ground.

RADIOMETERS

In general, any sensor that provides a measurement of total incident radiant energy can be classed as a radiometer. However, the term is most frequently applied today to instruments that measure radiation in the infrared or microwave region of the electromagnetic spectrum. The sensor measures brightness temperature, which, if the emissivity of the emitter is known, can be related to actual temperature. Radiometers are generally non-imaging devices that find their greatest applications in the determination of surface properties of large, relatively homogeneous areas. With spectral scanning capability and with the sun as a source, radiometers used in the absorption mode can contour the spectral line of a particular atmospheric constituent and can yield information on the distribution of molecules along the line of sight.

SPECTROMETERS

Instruments that disperse a spectrum and permit the scanning of frequencies by use of gratings or prisms are classed as spectrometers. A related instrument which also employs dispersive elements such as gratings and prisms but which presents all frequencies on a recording medium such as film is called a spectrograph. Although spectrometers are useful over a wide spectral range, the fact that most atmospheric pollutants have strong infrared spectra makes these instruments very attractive as remote sensors since the technology and components are highly developed. The efficacy of spectrometric techniques for pollution sensing is largely due to the fact that this approach is the basis for many laboratory and quality-control procedures in the process industries and many reference spectra have been carefully measured and recorded. The instruments can be used in either emission or absorption and afford a means of positive identification at reasonable cost.

INTERFEROMETERS

The main attraction of interferometers is their multiplexing character; i.e., the energy of the entire spectrum of frequencies within a signal are accepted at all times, as opposed to scanning instruments which at any time reject a large portion of the available energy. This feature, known as Fellgett's advantage, permits an interferometer to yield spectral information in a much shorter time than a scanning spectrometer or a spectrograph. Interferometers can also achieve very high resolving power if an adequate number of sampling points and accurate sampling measurements are provided.

The output of the interferometer is called an interferogram, which is the Fourier transform of the spectrum. This constitutes one of the chief disadvantages of this instrument, since considerable data processing must then be provided before the information in the interferogram is available in a useful form. Furthermore, this approach demands extreme precision, which cannot readily be maintained in many remote sensing applications without considerable packaging and operating considerations because of its extreme susceptibility to vibration distortions.

OPTICAL CORRELATION INSTRUMENTS

These instruments are ideally suited for sensing a pollutant whose absorption spectrum is known. They are not survey instruments since they depend upon matching or correlating the spectrum of the gas in question with the spectrum of an unknown sample in the same spectral regions. In its simplest form, an optical correlation monitor alternately passes a beam of light through a sample cell containing the gas being sought and a cell containing the unknown sample. Any difference in the transmitted light received at a detector can be related to the concentration of the subject pollutant in the sample. In more advanced forms, correlation instruments can utilize a filter whose transmission characteristics match the spectrum of the compound to be detected but which can be rapidly correlated. For example, plates with slits at appropriate locations or reproductions of spectra on transparent media have been used. Again the signal intensity is directly related to the degree of spectral correlation, hence to the concentration of the compound in question.

Optical correlation analyzers exhibit high sensitivity and high spectral resolution because of the multiplexing nature of the instrument. Its chief drawback is its high specificity which precludes the measurements of compounds whose spectra are not stored in the instrument. For remote measurement of pollutants, however, this is not a serious problem since the list of gaseous pollutants of concern in the atmosphere is not overly large.

LASER SYSTEMS

Development of the laser radar has provided an additional approach to remotely sensing the properties of the atmosphere. The technique is of special interest because it is one of the few active systems available for remote sensing. In its simplest form, the laser radar (lidar) uses a laser to generate a short, high-power light pulse. As the pulse propagates through the atmosphere, backscattered light is collected by a telescope, collimated by suitable optics, filtered by narrow band interference filters to decrease the intensity of the background light from the sky, and measured with a photomultiplier. The signal from the photomultiplier is fed into a suitable digital analyzer to provide a measurement of intensity of the light collectively backscattered by the atmospheric constituents as a function of altitude. The presence of particulate material can cause significant deviation from the echoes expected from a dust free atmosphere, and the presence of the particles can thereby be detected. Utilizing the spectral characteristics of molecular constituents of the atmosphere, it may also be possible by this basic technique to identify gaseous contaminants and determine their altitude profiles.

Typical range resolutions with presently available laser radar systems are of the order of 100 m. The first use of laser radar in the atmosphere was reported by Fiocco and Smullin (1963). A number of applications of the laser radar technique for detection of particulate matter have been investigated. Several investigators have demonstrated the ability of laser radar to accurately measure the height of maximum particle concentration and to monitor its temporal and spatial variation; measurements of this type can make a significant contribution to air pollution control and also to the verification of numerical models. Since laser radar can detect small changes in particle concentration, it is an excellent technique for observing the dispersal of particulate matter in stack plumes and also the dispersal of insecticides. The technique is directly applicable both to research problems in atmosphere transport processes and to operational problems.

PLATFORMS FOR REMOTE SENSING

TYPES OF AEROSPACE SYSTEMS

In this section, a number of aerospace systems will be described that illustrate some of the systems used in the past, or that may be used in the future, as platforms for remote measurements of pollution. The systems considered are (1) aircraft, (2) balloons, (3) sounding rockets, and (4) earth satellites. The gross mission parameters for each of the systems are summarized in Table I. Generally, the four systems have different operating altitudes and this is the basis for selection of a platform for a particular application. However, other considerations such as operating ranges, times, payload capacity, cost, and availability may dominate the decision-making process.

Airplanes have been used as platforms for remote sensors for many years, as witnessed by the extensive use of aerial camera techniques in map making and military reconnaissance. With its inherent flexibility and relatively low cost of operation, the airplane offers an ideal platform for many applications of remote sensing of pollution. Various remote sensors can be flown separately or in combination with point sampling instruments. Pollutant profiles in three dimensions can be made from an airplane by flying within, as well as above, the pollution envelope. Airplanes can respond quickly to random events or flights can be scheduled to observe predictable occurrences. They are particularly well suited to the problem of measuring the diurnal variations in pollution patterns. However, due to limitations of operating altitude and range, the airplane finds its greatest application in local or regional programs rather than in measurements on a global scale.

TABLE I

SUMMARY OF REMOTE SENSING PLATFORMS

PLATFORM	OPERATING ALTITUDE	OPERATING RANGE	OPERATING TIME	PAYLOAD WEIGHT
AIRPLANES	Less than 20 km	4000 km	5 hrs - 8 hrs	Less than 5000 kg
BALLOONS	20 km - 50 km	4000 km	24 hrs - 30 days	100 kg - 2000 kg
SOUNDING ROCKETS	40 km - 2000 km	5 km - 500 km	1 min - 5 hrs	1 kg - 200 kg
EARTH SATELLITES	200 km - 40,000 km	Global	Indefinite	10 kg - 30,000 kg

Balloons have traditionally been used for instrument platforms at altitudes above those obtainable by airplanes and below those obtainable by satellites. The high altitude balloon provides a relatively stable platform that is free of vibration and is capable of operating at high altitudes for long periods of time. The low acceleration during launch allows considerable choice in the selection of instrumentation. Compared with the cost of spacecraft operations, the cost of balloon operations is quite modest.

The targeting flexibility with balloons is considerably less than with airplanes, because of dependence on the prevailing winds for locomotion. However, by the use of precursory balloon flights and adjustment of altitude to capitalize on variations in wind direction, the path of the high-altitude balloon can be set with some degree of precision. Current techniques in balloon flight operations achieve targeting accuracies of 5 miles in 100 miles of flight path. Balloons using propulsive systems for station keeping capability are now in the planning stage.

Currently, there are three Federal agencies with active research programs utilizing high altitude balloon flights. These are the U. S. Air Force Cambridge Research Laboratories, the Office of Naval Research, and the National Center for Atmospheric Research. These agencies conduct as many as 100 balloon flights each year that can accommodate experiments from experimenters outside of their agencies. These balloon flights offer the opportunity for low-cost testing of experimental techniques that can utilize the unique test conditions offered in balloon flights.

Sounding rockets have been used extensively as platforms for *in-situ* measurements in the upper atmosphere, but have found only limited applications as platforms for remote sensors. Primarily, this is due to the limited operating times of the sounding rocket and the variations of altitude during the flight. While this variation of altitude is indispensable for vertical profiling by point measurement techniques, it constitutes an unwanted characteristic for most remote measurement applications. Despite these inherent limitations, the economics of operations, recoverable payload capability, and the possibility of simultaneous remote and point measurements make the sounding rocket a possible candidate for a number of remote sensing applications.

The techniques discussed so far have their greatest applicability where frequent measurements over limited areas are needed. On the other hand, earth satellite techniques are most applicable to measurements of long-lifetime phenomena with global implications. The viewing times and geographical coverage of satellite-borne remote sensors are governed by the orbital characteristics of the satellite. A practical lower limit on satellite altitudes of approximately 300 km is set by atmospheric drag. The upper limit on altitude is set by booster thrust capability and the gravitational field of the earth. The altitude of the spacecraft governs the selection of such sensor parameters as focal length, field of view, and spatial resolution. It also governs the period of rotation of the satellite about the earth and also the length of time that the instruments can view any particular location along the ground track. The inclination of the spacecraft orbit relative to the equator governs the latitude limits of the ground track, since the maximum latitude of the ground track of a satellite is equal to the angle that its orbital plane makes with the equator. A satellite with a 0° inclination traces a path along the equator; a 50° inclination would be needed for the ground track to cover the continental United States (excluding Alaska); a 70° inclination would carry the satellite over most of the populated world and would permit side viewing as far as the poles if the altitude is at least 450 km. A 90° inclination is necessary for complete global coverage with vertical viewing. Limits on orbital inclination are set by booster thrust capabilities, range safety requirements, and international political considerations. However, present rocket launch capability allows the launch of a satellite from the United States into almost any desired orbit. Generally, a satellite in a low-inclination low-altitude orbit experiences one sunrise and one sunset per orbit. This type of orbit is very useful for limb-scanning observations. At higher inclinations and altitudes, the satellite may remain in sunlight for a number of orbits without experiencing a sunset, or it may, in fact, remain continuously in sunlight for most of its lifetime.

Of the many potential orbits available to mission planners, two types of orbits have been favored in earth applications programs. These are the geosynchronous, or stationary, and the sunsynchronous orbits. A geosynchronous satellite is a satellite located in an equatorial posigrade (west to east) orbit with an orbital period equal to the earth's period of rotation. The altitude of such an orbit is approximately 35,900 km. The primary advantage of the orbit is that the satellite is stationary with respect to the earth. This allows continuous viewing of that portion of the earth within the line of sight of the satellite sensors. Disadvantages associated with this orbit include the extreme distance for earth viewing, the potential shortage of spacecraft parking space due to the uniqueness of orbital requirements, and the need to have several satellites to obtain global coverage.

The sunsynchronous orbit is an orbit selected so that the spacecraft passes over the same ground track at the same local time each day. This condition is satisfied by a family of near polar retrograde orbits with altitudes between 300 and 1,000 km. Such orbits have the advantage that data taking is standardized with respect to sun angle. In addition, many points on the globe receive coverage twice during each day: once on the illuminated side and once on the dark side. Since the sunsynchronous orbit is near polar, it provides nearly global coverage. The disadvantages of this type of orbit lie in the fact that diurnal effects at given points along the track are missed, and the orbital inclination is eliminated as a degree of freedom in mission planning.

SPACECRAFT CAPABILITIES

Table II lists the objectives and capabilities of some applications-type satellites in current and planned NASA spacecraft programs. The ATS, Nimbus, ITOS, SMS, and ERTS are automated-satellite programs. The Skylab is a manned earth orbiting laboratory plan for an early 1973 launch. The Space Shuttle is a concept for a reusable manned spacecraft, currently under study, with a projected operational capability for the late 70's or early 80's. These spacecraft reflect current spacecraft and sensor technology and indicate the types of platforms that may be available for future space flights for the remote measurement of pollution.

TABLE II
SUMMARY OF NASA EARTH SATELLITE PROGRAMS HAVING POTENTIAL FOR THE REMOTE MEASUREMENT OF POLLUTION

PROJECT TITLE	NASA NOMENCLATURE	OBJECTIVES	TECHNICAL DESCRIPTION		
				ATS D & E	ATS F & G
Applications Technology Satellite	ATS	To investigate and flight test technology common to a number of satellite applications; to investigate and flight test technology for the stationary orbit; to conduct a carefully instrumented gravity gradient experiment directed toward providing basic design information; and to flight test experiments for a number of types of satellite applications on each individual spacecraft.	Gross Weight, kg	793	930
			Instrument Wt, kg	97	272
			Investigations	Meteorological Communications, stabilization/pointing, and science experiments.	
			Power Watts	100	500
			Stabilization	Gravity gradient	Active
			Design Life	3 Years	2 Yrs.
			Launch Vehicle	Atlas-Centaur	Titan-III C
			Orbit	Geostationary	Geostationary
Nimbus	NIMBUS	To develop and flight test advanced sensors and technology basic to the study of the atmosphere and provide data for meteorological research; and to provide global collection and distribution of meteorological data.	Gross Weight, kg	66½	
			Instrument wt, kg	147	
			Investigations	*Meteorological*	
			Power (Instr), Watts	130 (Solar) 50 (Nuclear)	
			Stabilization	3 Axis	
			Design Life	12 Months	
			Launch Vehicle	Thor-Delta	
			Orbit	Circular Polar (1.111km)	
Improved Tiros Operational System	ITOS	To develop, procure, and launch, on a cost reimbursable basis for NOAA (Department of Commerce), a series of operational meteorological satellites based on Tiros research and development experience.	Gross Weight, kg	308	
			Investigations	Meteorological	
			Instrument Wt, kg	99	
			Power Watts	70	
			Stabilization	3-Axis	
			Design Life	6 Mo. min., 1 yr. goal	
			Launch Vehicle	Thor-Delta	
			Orbit	Circular (1,463 km)	
Synchronous Meteorological Satellite	SMS	To develop a geostationary satellite system which will meet the national operational meteorological satellite system (NOMSS) requirements as specified by NOAA; to flight test the satellites in orbit and when checked out turn them over to NOAA for operational use; and to continue research and development of geostationary satellite techniques as necessary to support the NOMSS.	Gross Weight, kg	243	
			Instrument Wt, kg	84	
			Investigations	Meteorological	
			Power, Watts	150	
			Stabilization	Spin Stabilized	
			Design Life	3 Years	
			Launch Vehicle	Delta - 1914	
			Orbit	Geostationary	

TABLE II—continued

SUMMARY OF NASA EARTH SATELLITE PROGRAMS HAVING POTENTIAL FOR THE REMOTE MEASUREMENT OF POLLUTION

Earth Resources Technology Satellites	ERTS	To design, develop and launch a series of spacecraft into medium altitude orbits for the purpose of conducting a variety of experiments in the earth resources disciplines.	Gross Weight, kg	816
			Instrument Wt, kg	204
			Investigations	Earth Resources
			Power, Watts	500
			Stabilization	3-Axis
			Design Life	12 Months
			Launch Vehicle	Delta-N
			Orbit	Circular Polar, Sun-Synchronous 912 km
Earth Resources Experiments Package For Skylab "A"	EREP	To develop techniques for selective use of remote sensing instrumentation capable of detecting the visible, infrared, and microwave radiation emitted and/or reflected by the earth and to study the applicability of these measurements for quantitative analysis of earth resources; and to perform correlative studies using ERTS and airborne sensors leading to a definition of the role of manned systems in earth resources surveys.	Gross Weight, kg	975 (total package)
			Sensor Weight, kg	420
			Investigations	Visible, Thermal Infrared, and Microwave Emissions from Earth
			Power, Watts	170 (Average)
			Design Life	8 Months
			Launch Vehicle	Saturn V
			Orbit	Circular, 435 km, 50° Inclination
Space Shuttle	SPACE SHUTTLE	To develop a reusable manned space vehicle to provide an economical means of delivering payloads to orbit, to provide the capability of man-controlled in-orbit operations; and to provide the capability of visiting satellites and returning satellites from orbit.	Orbiter Payload Gross Weight, kg	29,500 for Design Mission of 28.5° Inclination, 185 km alt. 18,200 For Reference Mission Of 90° Inclination, 185 km Alt. 11,300 For Reference Mission Of 55° Inclination, 500 km Alt.
			Sensor Weight, kg	T. B. D.
			Investigations	T. B. D.
			Stabilization	± 0.03°/Sec All Axes
			Design Life	Orbiter will have 7-30 day orbital stay time capability, shuttle-delivered free-flying payloads design life T. B. D.
			Launch Vehicle	Recoverable, Reusable Shuttle

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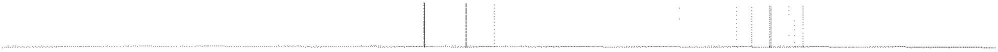
SECTION II

GASEOUS POLLUTANTS AND NATURAL TRACE GASES

A. Barringer
J. Becher
C. Farmer
J. Gille
***G. Grew
P. Hanst
*W. Kellogg
A. Lefohn
C. Ludwig
J. Ludwig
W. Matthews
D. Pack
T. Pepin
**J. Russell, III
H. Yates

*Chairman of Panel
**Associate Chairman
***Assistant Chairman



SECTION II

GASEOUS POLLUTANTS AND NATURAL TRACE GASES

INTRODUCTION

Early notice of the effects of air pollution was due to smoke and smog, that is, the visible aerosols. However, it is now known that many of the damaging effects arise because of the generally invisible gaseous constituents. Some gases, like the toxic gas carbon monoxide, cause only a direct effect. Other gases, such as sulfur dioxide, can participate in the formation of secondary constituents which are also undesirable. For example, it is now recognized that sulfur dioxide reacts with oxygen and water vapor to form the highly toxic and corrosive sulfuric acid vapor.

Besides these short term effects, gaseous pollutants on a global scale could lead to modification of man's environment. A case in point is carbon dioxide. This gas, which plays a significant role in the global heat balance, is currently believed to be increasing in concentration due to man's use of fossil fuel. (SCEP, 1970; and SMIC, 1971) If this increase is allowed to continue, it is possible that the global heat balance could be upset, leading to climatic change.

These are only a few of the effects discussed in the SCEP (1970) and SMIC (1971) reports which may occur when gaseous pollutants are added to the atmosphere. Although many of the factors involved are not well understood and partly speculative, it is clear that man must attempt to understand these processes in order to establish guidelines for future actions. Since these phenomena take place in a very dynamic environment and, in some cases, in remote areas of the globe, it is expected that remote sensing will play a vital role in this important study.

The potential of remote sensing as an aid in studying the atmosphere has been recognized for many years. One of the first papers discussing remote detection of atmospheric parameters from satellites was presented by King (1956). Later, after the first artificial earth satellite was launched, widespread interest developed in remote sensing, and today an exhaustive list of references exists on the subject.[1] The principal emphasis in the past has been on the measurement of atmospheric temperature, water vapor, and ozone—in addition to the obvious observation of cloud distribution. The practicality of remotely detecting these parameters has been clearly demonstrated through results of the Nimbus 3 and Nimbus 4 satellite experiments (see for example, Wark, 1970; Ellis et al., 1970, and Conrath et al., 1970). These experiments were based on measurements taken in the infrared region of the spectrum. Similar research has also been conducted using backscattered ultraviolet energy to detect ozone (see for example, Dave and Mateer, 1967; Anderson et al., 1969), and research is under way in the use of microwave energy to detect temperature and water vapor (see for example, Barrett et al., 1966; Staelin, 1969; Toong and Staelin, 1970). This body of work provides a sound base for the development of methods for the remote detection of air pollution, since similar methods can be applied and extended.

The purpose of this report is to review the gaseous air pollutant problems and means of remote detection of these gases with the hope of promoting further work where it is necessary and stimulating new research where it is appropriate. The problems caused by various pollutant molecules and specific measurement requirements needed for each gas in order to study the effects are discussed. A number of measurement approaches and instrument techniques are described. These include methods that have been used as well as some new techniques that appear promising. The section entitled "Measurement Capabilities" lists current measurement capabilities for each gas. Some gases have already been measured by satellite borne instruments, while for others there is no known technique capable of remotely measuring their concentration. All of these gases are specifically noted. The last section includes recommendations for future research.

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[1] See Wark and Fleming (1966) and references therein for a historical review. See the Report of the Study Conference on GARP (ICSU/IUGG-CAS) (1967), Conrath (1967), National Academy of Sciences (1969), and Gille (1968a) for a discussion of various techniques and approaches to the problem.

PROBLEMS AND MEASUREMENT REQUIREMENTS

INDIVIDUAL GASES

A variety of effects must be considered in identifying gaseous air pollution problems. These range from biological effects on man and animals to effects on the global environment. In some cases, naturally occurring gases whose concentrations are being altered due to man's activities may be considered problems. Notable examples of these gases are ozone, water vapor, and carbon dioxide. Alteration of the natural levels of these constituents could have serious biological and environmental consequences. Other forms of pollution arise due to man's addition of foreign trace gases to the atmosphere. It is difficult to predict the exact effects resulting from these gases. The atmosphere has a long response time, and in most cases it would take years for any environmental changes to become apparent.

When considering biological effects on man, it is hard to distinguish the effect of pollution from among the many other factors that normally contribute to a given physical condition. Nevertheless, studies have been conducted and estimates have been made of the consequences of adding various types of pollutants to the atmosphere. Smog episodes have also occurred (see Stern, 1968, Vol. I) providing direct indications of pollution levels that can cause severe problems under given meteorological conditions. The results of these studies and events have established the sources of most pollutants and provided information on the importance of various gases as pollution problems.

The remainder of this section summarizes current knowledge of these problems. The term "gaseous pollutant" is taken here in the broad context to mean 1) any naturally occurring constituent whose concentration is being changed due to man's activities, with an accompanying biological or environmental effect and 2) any gas that is not present in normal clean air.

Carbon Dioxide

Carbon dioxide is an important atmospheric constituent because of the dominant role it plays (along with water vapor) in setting the thermal balance of the atmosphere and hence the temperature at the surface of the earth. Its natural sources are respiration, volcanic and other geological emissions, and the decay of vegetation. It is removed from the atmosphere by absorption in the oceans, by mineralogical differentiation, and by photosynthesis. The natural processes of production and reabsorption or destruction are assumed to be fairly closely balanced, the mean "normal" atmospheric abundance before the Industrial Revolution being approximately 290 ppm. (PSAC, 1965) However, relatively small changes in sea-surface temperatures or significant changes in terrestrial forest areas could shift this balance. CO_2 appears to be uniformly distributed (in clean air) over the globe to within 1 ppm. Observations made over the past 12 years show a seasonal variation of about 6 ppm in the mixing ratio, the maximum occurring in late spring (Pales and Keeling, 1965). The lifetime in the atmosphere is estimated (Robinson and Robbins, 1969) to be 1.9 years in the Northern Hemisphere and 3.9 years in the Southern Hemisphere.

The injection of large quantities of additional CO_2 into the atmosphere by the burning of fossil fuels poses a potential threat in terms of its influence on the heat balance of the earth-atmosphere system. The CO_2 concentration appears to be increasing at a rate of 0.2%, or 0.7 ppm, per year, and it is believed that this increase is directly the result of man's activity. Estimates of the effect of the increase on the radiation balance, based on extrapolation at the present rate, indicate that by the year 2000 the mean surface temperature will have risen by 0.5° C. The computations do not include the effects of atmospheric dynamics on the exchange of heat nor the compensating effects of increased evaporation and cloudiness; their neglect renders uncertain the predicted effects due to changes in the CO_2 content of the atmosphere. A fuller discussion of this topic can be found in the SCEP (1970) report.

The total vertical abundance of CO_2 should be monitored on a global scale, and on a long term basis. The accuracy of these measurements should be such that yearly changes of 0.5 ppm in the average mixing ratio can be determined. In view of the difficulty in determining accurately the absolute CO_2 abundance by remote sensing on a global scale (see section entitled "Measurement Requirements"), these measurements should be correlated with *in-situ* measurements made at ground level by a network of monitoring stations.

Carbon Monoxide

The global budget of CO is uncertain, because the production rates of all sources and the removal rates of all sinks are uncertain. Robinson and Robbins (1969) have estimated the yearly emission from anthropogenic sources to be 274 million tons and from natural sources 75 million tons. They list, as natural sources, forest fires, surface waters of the oceans, and photochemical reactions of terpenes. An additional source has recently been discussed by Swinnerton et al. (1971), who discovered a supersaturation of CO in rainwater and attributes the production of CO to the photochemical oxidation of organic matter and/or the slight dissociation of CO_2 induced by electrical discharges. The conjecture that the surface waters serve as a source has recently been strengthened by Wilson et al. (1970) who produced CO (in addition to ethylene and propylene) in illuminated sea water and also distilled water to which dissolved organic matter from phytoplankton was added. The sinks are believed to be the stratosphere (Seiler and Junge, 1970; Pressman and Warneck, 1970) and the soil (through bacterial action) (Robinson and Robbins, 1969). Westberg (1971) has identified a possible removal mechanism in photochemical smog which involves the net reaction $CO + O_2 + NO \rightarrow CO_2 + NO_2$. Also, Levy (1971) has suggested in a steady-state model of the normal (unpolluted) surface atmosphere, that radicals and formaldehyde are formed, which in turn may be responsible for the rapid removal of CO, leading to a CO lifetime as low as 0.2 years. This lifetime is much less than the three years or less suggested by Robinson and Robbins (1969).

Since these questions are unresolved and since the potential for a CO build-up exists, global monitoring of this species should be conducted in the troposphere. CO is believed to be uniformly mixed through the troposphere at levels of 0.05 to 0.1 ppm; thus a minimum measurement accuracy of 0.01 ppm is believed to be necessary. Because the CO concentration may be largely affected by man's activities, it also seems necessary to provide regional coverage.

As far as CO in the stratosphere is concerned, Hays and Olivero (1970) have postulated a reaction scheme which indicates that the mixing ratio of CO_2 may decrease, and that sufficient quantities of CO are produced as a product of CO_2 photodissociation to be aeronomically significant.

Sulfur Dioxide

Sulfur dioxide is important as a pollutant on both a global and regional scale. Its global importance is due to the role it plays in the formation of stratospheric aerosols. Rosen (1971) has shown that the primary component of aerosols in the stratosphere is sulfuric acid which is derived from SO_2. Thus the problem of global climate change is related to the stratospheric SO_2 concentration.

Sulfur dioxide is recognized as a pollutant on a regional scale because of its toxicity, its damaging effect on plants, and because of its contribution to particle formation with attendant visibility reduction and the formation of "acid rains".

Natural sources of SO_2 include oxidation of H_2S and emission from volcanos. The single most important anthropogenic source is coal-fired boilers for electric power generation, which accounts for about fifty percent of the total yearly emission from all sources both natural and man-made (Kellogg et al. 1971). The lateral distribution of SO_2 depends strongly on the source location since the atmospheric residence time is probably less than one week, according to Robinson and Robbins (1969). These authors also point out that a hemispheric imbalance exists and that by making global measurements in the Northern and Southern Hemispheres, the influence of SO_2 pollutant emission on atmospheric parameters may be studied. According to Georgii (1970), most of the total burden of SO_2 is found in the first kilometer above the earth's surface.

In order to inventory stratospheric sulfur dioxide, it is recommended that the seasonal mean be determined over 10-degree latitudinal belts with vertical resolution of the order of a kilometer in the altitude range of the sulfate layer and with an accuracy of 0.5 ppb. It is recommended that the total burden be monitored seasonally with spatial resolution at the surface of 100 km^2 and with an accuracy of 10 ppb.

Hydrogen Sulfide

The importance of this species lies in its oxidation to SO_2. A secondary removal process is rainfall. Although natural sources are uncertain, it is believed that the yearly emission of about 100 million tons (94 percent from natural sources) comes mainly from the decomposition of organic matter (Kellogg et al., 1971). Atmospheric background values are also uncertain because of lack of data. Robinson and Robbins (1969) give a value of 0.2 ppb and a lifetime of 2 days. So little is known about this gas that it is difficult to establish measurement requirements. A requirement was adopted that the lower atmosphere measurement be accurate to one-half the background value or 0.1 ppb. Unfortunately, measurement requirements for several other pollutants were based in part on subjective factors because of our poor state of knowledge concerning these gases.

Ozone

Ozone has probably been studied more than any other atmospheric constituent. Most of the ozone is found in the stratosphere, where it is produced naturally, but it is also present in the troposphere from natural and, especially, man-related causes. These will be discussed separately.

Ozone in the stratosphere is important because it shields life on earth from lethal ultraviolet radiation and because it partly controls stratospheric temperature. Ozone is naturally produced by photochemical reactions now believed to involve water vapor and the oxides of nitrogen (Crutzen, 1971). Because many of the rate coefficients are poorly known, the exact reaction scheme is highly controversial at this time. The vertical partial pressure profile is roughly Gaussian with a peak between 25 and 30 km, where the mixing ratio is about 8 ppm. The concentration profile is a highly variable function of latitude, longitude, day, and season. Excellent summaries of current knowledge of atmospheric ozone have been published by Craig (1965), Vassey (1965), and Griggs (1966).

The SMIC (1971) report notes that ozone measurements at many places over the globe have indicated increases in total ozone of a few percent over a decade. These are believed to be natural fluctuations, but their occurrence cannot be explained, nor can it be certain that the transport of man-produced materials from the troposphere has not had an effect.

Ozone is mixed from the stratosphere into the troposphere, and is produced locally by factory smoke, forest fires, lightning, and volcanic eruptions and through chemical reactions involving nitrogen dioxide, nitric oxide, and hydrocarbons in the presence of sunlight. Normal surface level ozone concentrations are about 10 ppb. However, concentrations as high as 500 ppb have been recorded during smog episodes (Project Clean Air, 1970). Ozone is toxic, and irritation to man has been observed for concentrations as low as 100 ppb.

In view of the importance of stratospheric ozone to life on earth, it is important that any changes in total ozone be monitored, and causes be identified. The yearly average of total ozone should be determined to 1%, preferably so as to provide global maps of mean annual total ozone. To study causes of variation, ozone profiles should be measured with a vertical resolution of a few kilometers and an accuracy of about 10%. Diurnal and seasonal variations should be measured. In order to monitor and map tropospheric ozone on a regional basis, a measurement accuracy of 10 ppb is required, preferably with daily coverage.

Stratospheric Water Vapor

The major sources of water vapor are at the earth's surface, where there is an average concentration of about 1000 ppm in the atmosphere. In the lower stratosphere the water vapor concentration is very low, and in the period 1964 to 1971 has increased from 2 to about 3 ppm (Mastenbrook, 1968, 1971; Harrison, 1970). The dryness is probably due to the cold tropical tropopause that functions as a natural cold trap.

Although the concentration is very small, water vapor and its photolytic products are important in the photochemistry of ozone formation and destruction. Water vapor also contributes to the radiative balance of this region; more water vapor will lead to greater cooling and lower stratospheric temperatures. Because of the deliquescence of sulfuric acid, water vapor also plays a role in the formation of stratospheric aerosols. The importance of these particles to the stratospheric or global heat budget is not yet clear.

In order to monitor the amount of water vapor in the stratosphere and detect any significant changes, it is necessary to measure stratospheric water vapor concentrations to at least 0.5 ppm. Because of its roles in both ozone photochemistry and aerosol formation, the water vapor concentration profiles should be determined with a vertical resolution of a few kilometers. Rapid time changes are not anticipated, but global mapping is desirable.

NITROGEN COMPOUNDS

The nitrogen compounds have a central role in the photochemical air pollution problem. They interact with each other as well as with oxygen, hydrocarbons, sulfur oxides, carbon monoxide, and water. The urban photochemical pollution problem has its beginning in the fixation of nitrogen during combustion. The pollutants containing nitrogen are NO, NO_2, N_2O_4, N_2O_5, N_2O, HNO_2, HNO_3, NH_3, NO_3, and the organic peroxynitrates (PAN's). Robinson and Robbins (1969) show that the nitrogen cycle is basically made up of three individual cycles involving N_2O, NH_3, and the NO-derived compounds. There is very little interaction between the cycles. Figure 1 from their report illustrates soil and marine circulation of nitrogen compounds in tons per year. The important nitrogen pollutants are discussed under the following five items.

Nitrogen Oxides (NO_x)

On a global scale, the presence of nitrogen oxides is of concern since they may lead to changes in the stratospheric chemical balance, especially as regards ozone (Johnston, 1971). In the lower atmosphere, nitrogen oxides lead to plant damage and they are toxic at ppm concentrations. They are also involved in the formation of particles and in the production of photochemical smog with all its well-known undesirable effects such as reduced visibility and eye irritation.

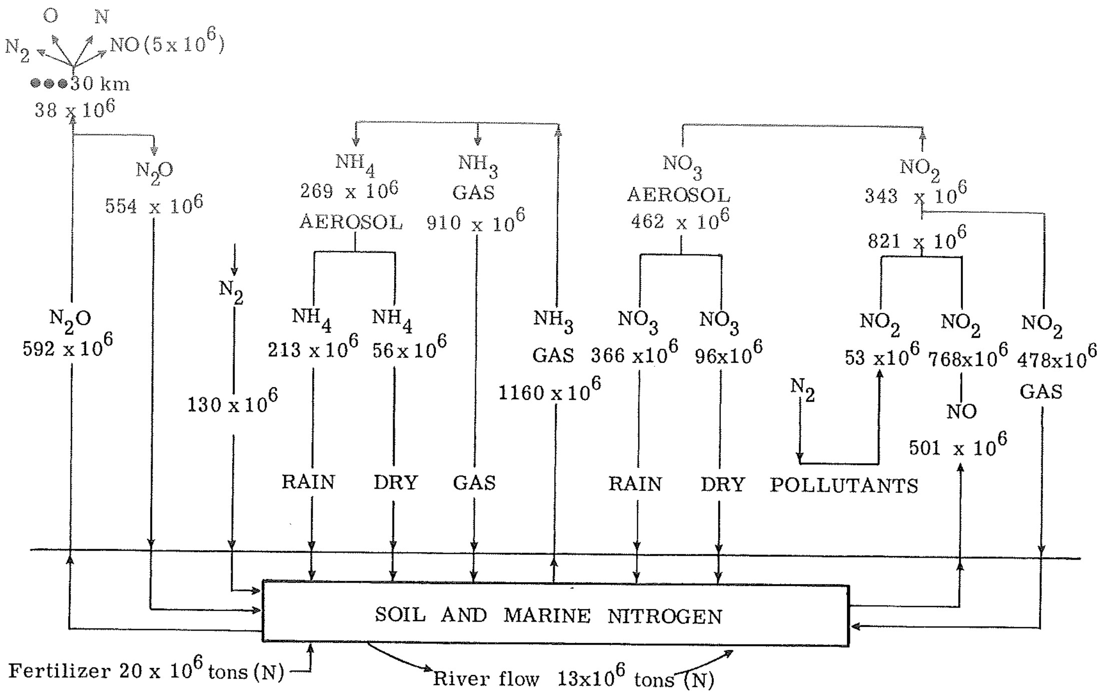

Figure 1.—Environmental circulation of nitrogen compounds, tons per year.
(After Robinson and Robbins, 1969.)

On a world wide basis, about 95 percent of the nitrogen oxides originate as NO from biological activity in the soil. (Robinson and Robbins, 1969). The remaining 6 percent comes mainly from nitrogen fixation occurring at high temperature during combustion of oil, gasoline, coal, and natural gas. Nitric oxide reacts in the atmosphere, and proceeds up the oxidation scale in a series of chemical changes. A discussion of reactions involving the nitrogen oxides is contained in Project Clean Air (1970) and also in Leighton (1961).

In order to monitor nitrogen oxides in the atmosphere and to observe their effects it will generally be necessary to measure concentrations of about ten ppb; and the concentrations should preferably be obtained as functions of altitude. In studying plant damage effects, an accuracy of 0.1 ppm would be sufficient, since the threshold for biological effects seems to be at ppm concentrations.

Ammonia

Ammonia is a major link in the formation of aerosols and thus may affect the heat balance. Its rapid interaction with SO_2 in the atmosphere creates large particles (0.1 μm to 10 μm and larger). The removal of SO_2 limits the formation of toxic H_2SO_4.

Ammonia production is mainly in soil from the decay of vegetation and animal matter. Man's contribution, from combustion processes and chemical manufacturing, amounts to less than 1 percent globally.

The background values for NH_3 are uncertain (6-20 ppb). Measurements should be performed on a regional basis with an accuracy of 10 ppb within the first km.

Nitrous Oxide

The dissociation of N_2O ($N_2O + h\nu \rightarrow N + NO$ and $N_2O + h\nu \rightarrow N_2 + O$) may be a significant factor in the chemistry of the stratosphere. The rate of photodissociation has not been firmly established but data taken by Schutz et al. (1970) are in support of rates calculated by Bates and Hays (1967). The global budget of N_2O is not yet understood. Schutz et al. (1970) have suggested that oceanic sources and air mass movements over dry land might affect this budget. The background value of N_2O is about 250 ppb. However, measurements should be accurate to about 50 ppb.

Nitric Acid

Nitric acid is an important pollutant in the atmosphere because of its possible role in the formation of aerosols and the accompanying removal of NO_2. This gas was discovered in the atmosphere by Murcray et al. (1969), using infrared observations made from a balloon at 30 km with an instrument aimed at the sun during sunset. Rhine et al. (1969) made estimates of the HNO_3 content using the data of Murcray et al. (1969) and since that time Murcray (1971) has published results of other flights. It appears that HNO_3 is layered much like ozone and is located primarily in the stratosphere from 10 to 50 km with a maximum mixing ratio of about 0.01 ppm. These results suggest a possible correlation between nitric acid and ozone concentration. Simultaneous measurements of nitrogen dioxide, ammonia, water vapor, ozone, nitric acid, and aerosols in the lower stratosphere would be useful in studying the chemistry of the stratosphere. In this regard, Gille and colleagues have proposed a satellite experiment using infrared measurements of the horizon to measure, among other things, the concentration of water vapor, ozone, and nitric acid in the lower stratosphere. A measurement accuracy for HNO_3 of 1 ppb is desirable.

Peroxyacyl Nitrates (PAN's)

The organic peroxynitrates, generally called PAN's, are a class of compounds formed in urban air that are responsible for some of the major undesirable effects of smog, such as eye irritation and plant damage. The abbreviation PAN describes the accepted structural formula of the smallest and most abundant member of the class—peroxyacetyl nitrate, $CH_3(CO)OONO_2$.

The PAN-type compounds were not known prior to their discovery in air pollution studies. They have no known applications in chemical technology. Recently the related compound peroxybenzoyl nitrate (PBZN) has been discovered in photochemical reactions of air pollutants; and PBZN has been shown to be many times more irritating to the eyes than PAN (Heuss 1968). The discovery and identification of PBZN were made by means of its infrared absorption spectrum.

The PAN compounds are surprisingly stable in the atmosphere in view of their chemical structures. Their removal rates have not yet been accurately measured, but it is suspected that they can persist into the night and possibly into the next day. They are not readily photolyzed by sunlight. A recent review of their properties has been published by Stephens (1969).

On a regional basis, it may be of interest to measure the spreading of PAN from urban centers. Probably this can best be done by groundbased sensing systems, but it is conceivable that remote sensing systems could detect the distinctive infrared bands. It seems highly unlikely that the PAN compounds can last long enough to reach the stratosphere or be distributed on a global basis. A measurement accuracy of from 1 to 10 ppb is required.

Fluorocarbons

Fluorocarbons such as the Freons are considered as relatively harmless. Chemically they are extremely inert, which is the reason that they are used so freely as propellants in aerosol cans. One may encounter them in food, in cosmetics, and even in medicinal preparations. They are used as working fluids in refrigerators and have been considered for use as working fluids in Rankine-cycle (external combustion) engines. So much usage implies that the fluorocarbons are being added to the atmosphere at an ever-increasing rate. A related substance also being used more and more widely is sulfur hexafluoride, which is used as an insulator in transformers, transmission lines, and other electrical devices.

The inertness of these compounds, which is their virtue in most applications, is also the cause for environmental concern. In addition to being chemically inert, the fluorinated compounds are optically inert. Photo-dissociation requires very short ultraviolet wavelengths, which are available only at the highest levels of the atmosphere. At present there does not seem to be any known mechanism for removal of this class of fluorinated compounds from the atmosphere. Accumulation can therefore be expected to continue, resulting in an apparently irreversible alteration of the atmospheric composition. Clearly, this situation is cause for concern. It is recommended that the physical and chemical properties of the fluorinated compounds be studied further and their atmospheric concentrations be monitored.

At present the concentrations of these compounds are not likely to be greater than the parts-per-trillion level. Such concentrations are detectable by the sensitive electron-capture technique, but are well below the detectability level of space-borne optical systems. However, the fluorocarbons have distinctive strong infrared bands, and can be expected to become detectable optically when their concentrations approach the parts-per-billion level. A measurement accuracy of better than 0.001 ppb may be required.

Halogens and Halogen Compounds

Both free halogens and halogen compounds are widely distributed as trace constituents in the lower atmosphere. Iodine vapor has been studied in the greatest detail and is normally always present at ground level at a concentration of about 1 part per billion. Other halogens that have been reported in free form include bromine and chlorine (Goldschmidt, 1962). None of the free halogens are known to constitute a toxic pollution problem at their normal low ambient concentrations. However, they are of some interest because of their regional associations.

Iodine is concentrated in many marine organisms by as much as 100,000 times the background concentrations in sea water, and there is a liberation of iodine vapor by marine plants and organisms to the atmosphere at the ocean surface (Barringer, 1970). The presence of iodine vapors can therefore potentially be used as an indicator of marine bioproductivity. There is a related occurrence of iodine vapor over some oil fields, attributable to the marine biogenic origin of the petroleum. Sedimentary rocks associated with oil accumulations are often rich in iodine and have been demonstrated to contribute iodine to the atmosphere if exposed at the surface. The distribution of iodine in soils is of health significance due to the close association between the incidence of goitre and regional iodine deficiencies. Since the distribution of atmospheric iodine can be related to the underlying soil, the remote sensing and mapping of iodine concentrations from satellites could be applied to the identification of iodine-deficient regions.

There are similar biological and geological relationships for bromine. Leaded-fuel additives account for the release of significant amounts of bromine to the atmosphere in urban areas.

An investigation carried out by Chamberlain (1951) indicates that free iodine released to the atmosphere may be rapidly absorbed by naturally occurring particulates, leaving only a fraction in free form. A similar situation probably exists with the other halogens. The halogens possess strong optical absorption bands well suited for remote sensing, but only the free and nonabsorbed fraction can be so detected. Therefore, some caution is required in interpreting published concentration figures determined by optical remote sensing techniques.

HF and HCl are both pollutant gases which can be troublesome in some urban and industrial areas. HF effluents are generated in the manufacture of phosphate fertilizers and in aluminum refining. Fluoride poisoning in both man and animals has not been uncommon in the vicinity of such pollutant emitting sources. In addition, certain types of plants and crops are very sensitive to fluorides. HCl is liberated by the incineration of PVC type plastics, and increasing amounts are being dispersed in urban environments. Measurements of these gases should be accurate to about 1 ppb.

Methane

The main source of methane in the atmosphere is decomposing organic matter, especially in swampy areas (Enhalt, 1967). The natural background is about 1.4 ppm. Little is known about the vertical distribution, but indications are that the mixing ratio is virtually constant up to about 20 km (Bainbridge and Heidt, 1966), and very low at about 50 km (Scholz et al., 1970). It is believed to be oxidized to water vapor and carbon dioxide in the stratosphere (E. A. Martell of the National Center for Atmospheric Research) and may be involved in the ozone photochemistry. Its primary importance is in its contribution to the production of stratospheric water vapor. However, it may also be important in photochemical reactions in the lower atmosphere.

To monitor changes in methane and to study its sinks in the stratosphere, a measurement accuracy of 0.2 ppm with a vertical resolution of a few kilometers is required. Global maps of vertical profiles will be needed, but probably not more frequently than once every few days. Measurements in the lower atmosphere should be accurate to about 0.5 ppm.

Formaldehyde

Formaldehyde is formed in photochemical smog and is an irritant; accordingly, it should be measured on a regional level. On a global scale, its formation in the unpolluted atmosphere has been postulated by Levy (1971) to occur due to reactions involving the radicals OH, HO_2, and CH_3O.

The daytime concentration is calculated to be 2 ppb; thus the required measurement accuracy should be about 1 ppb in the lower troposphere.

Other Hydrocarbons

Hydrocarbons with two or more carbon atoms are primarily man-made pollutants. Losses of gaseous or volatile liquid fuels, incomplete oxidation and cracking of fuels in combustion, and emissions from chemical manufacturing plants introduce a variety of hydrocarbons into the atmosphere. The motor vehicle contributes 16×10^6 tons per year, accounting for roughly half of the total emission. The other major sources are industrial processes accounting for 15 per cent, organic solvent evaporation 10 per cent, forest fires 7 per cent, agricultural burning 5 per cent, and solid waste disposal 5 per cent (H.E.W., 1970). These gases are modified by photochemistry in the atmosphere and are subsequently removed by rain storms. A number of hydrocarbons contribute to the formation of ozone in the presence of nitrogen oxides and sunlight. Thus, they contribute greatly to the creation of photochemical smog in the lower atmosphere. The different classes of hydrocarbons have different degrees of reactivity in the formation of smog. Olefins are the most reactive, aromatics next, branched-chain paraffins next, and straight-chain paraffins are the least reactive. No hydrocarbons, other than methane, have been detected in the high atmosphere. However, if sufficient quantities are injected into the stratosphere, they may influence aerosol formation.

It seems likely that the natural sources of methane may also emit ethane and other hydrocarbons. However, the relative proportions emitted must fall off very rapidly with increasing number of carbon atoms. In order to estimate the contributions of natural sources, global and regional distributions of gases such as ethane and propane should be studied, but for the present the measurements should only be made at ground level. A detectability of 1 ppb may be necessary in order to distinguish species.

Mercury

Mercury is present as a vapor at all times in the lower atmosphere at concentrations between 1 and 10 nanograms per cubic meter. This mercury is derived from the natural background of mercury present in the soil and in the biosphere.

Contributions of mercury to the atmosphere are made by certain industrial operations, notably the manufacture of chlorine by the chlor-alkali process. Mercury rich plumes from industrial operations can sometimes be traced for many miles in the atmosphere. The mercury in these plumes is eventually lost to the ground by processes of absorption and wash-out.

Ambient atmosphere concentrations of mercury vapor on a regional scale are always below toxic levels for man, but the cumulative contribution by mercury vapor to mercury levels in soil, vegetation, and water around polluting industries may be important.

Mercury in soils, lakes, and streams is subject to methylation by a number of common microorganisms, and it thereby becomes considerably more toxic. Mercury dispersed in the environment both in air and water is strongly accumulated by fish, birds, and other forms of life, particularly when in the form of methyl mercury, and is therefore a highly undesirable pollutant. A general discussion of mercury in the environment can be found in a U. S. Geological Survey report published in 1970. Measurements should be accurate to 0.01 ppb in initial studies of this gas.

Heat Released

It is clear that man can directly heat the atmosphere over his industrial complexes, and as the production of energy and the burning of fossil fuels increase the area affected will increase also. Already the release of heat over areas as large as 10^4 to 10^5 km^2 is approaching 10 percent of the net solar radiation absorbed by the ground. In the next fifty years or so, with a further extension of industrialized areas, we can expect to find areas of 10^3 to 10^4 km^2 where the heat released is equal to the net solar insolation, and over entire continents it may amount to 1 percent of solar heating (SMIC, 1971). Such a massive heating may very well be a significant factor in determining the climate of a hemisphere; and it is already recognized as a cause of local climate change in some instances.

Since this kind of heat release into the environment is often referred to as "thermal pollution", we are including it in our list of pollutants, even though it has a very different character from the gases with which we are mostly concerned. We are not even sure that it needs to be measured *remotely*, although many aspects of it could be. The reason for this statement is that, in considering climatic effects, we are not concerned with day-to-day or even year-to-year changes in the heat released in a given region. Rather, we are concerned with the long-term trend over decades and, perhaps more important, with detecting the *effects* that may result. Many of these effects will probably be rather subtle changes in the environment and the climate. This probably calls for more detailed observations than can be achieved remotely, and over a fairly long period of time.

MEASUREMENT REQUIREMENTS

Pollutants were divided into two groups in defining measurement requirements. One group includes gases that have a recognized environmental impact; the other group includes those for which concern is of a speculative or long-term nature. The problem for each pollutant was identified and the geographic region that would be influenced by the problem was determined. Problems of global concern were placed in one grouping and those affecting only regions of the globe were included in a second grouping. Regional problems were considered to be those having a scale of about 10^6 square kilometers. Local problems were not identified in this study. Tables I and II list the various gases, the associated problems, and the measurement accuracies considered to be necessary in order to study the problems by remote sensing techniques. The difficulty in establishing measurement requirements is again emphasized. The problems arise because of our primitive state of knowledge concerning the pollutants and because of the complexity of the interactions of pollutants with the atmosphere, the oceans, the biomass, and man. Because of this, many of the accuracy requirements given in the tables were based in part on subjective factors.

Most remote sensing techniques applicable to spacecraft observation of pollutant gases in the troposphere measure a quantity related to the total burden of gas in a vertical column extending upwards from the earth's surface. The units that are therefore most appropriate to these measurements are mass of gas per unit area of the earth's surface, integrated thickness of gas at standard temperature and pressure (STP), or (parts per million) x (meters) representing a product of concentration and thickness (STP). In the normally accepted terminology used in air quality measurements, units of absolute concentration in parts per million or parts per billion (by volume) are employed. These usually refer to ground level concentrations.

In attempting to adapt this accepted terminology of ground level measurements to remote sensing measurements from aircraft and spacecraft one may use a concentration figure by assuming that the vertical gas burden is distributed uniformly throughout a given thickness. If this approach is adopted, it is desirable to use two standard thicknesses; namely a layer 1 km thick for short-lived ground generated pollutants and a layer 8 km thick (one scale height) for gases of the well-mixed class. Examples of gases that are well mixed through the vertical column of the atmosphere are CO_2, CO, H_2O, O_3, and CH_4. Other pollutant gases such

TABLE I

REQUIREMENTS FOR MEASURING POLLUTANTS WITH A RECOGNIZED ENVIRONMENTAL IMPACT

CONSTITUENT AND REGION OF THE ATMOSPHERE	GLOBAL	
	PROBLEM: Why are we concerned?	Accuracy
CO_2	Measure its increase, which is a factor in climate change	0.5 PPM
SO_2 - UPPER TROPOSPHERE AND STRATOSPHERE	Formation of particles in the stratosphere from SO_2 carried upward from the troposphere or injected by volcanos and SST's	0.5 PPB
O_3 STRATOSPHERE	What causes the long term changes in distribution of ozone? Is there a correlation with solar activity?	TOTAL CONTENT 1% DISTRIBUTION WITH HEIGHT 10%
H_2O STRATOSPHERE	(a) Determination of effect on ozone concentration (b) Determine effect on radiation balance of stratosphere (c) Determine influence on particle size distribution in the sulfate layer	TOTAL CONTENT 20% for (a) Much less accuracy for (b) DISTRIBUTION WITH HEIGHT 0.5 PPM for (c)
NO_x STRATOSPHERE	Determine effect on ozone concentration	NO_2 and NO 10 PPB
CONSTITUENT IN LOWER LAYERS	REGIONAL	
	PROBLEM: Why are we concerned?	Accuracy
SO_2	(a) Damage to plants (b) Particle formation which subsequently contributes to acid rain	10 PPB
H_2S	(a) Oxidizes to SO_2 (b) Its natural source is uncertain	0.1 PPB (?)
NO_x	(a) Damage to plants and toxicity at PPM concentrations (b) Photo-oxidation of hydrocarbons and particle formation (c) Precursor of PAN's	0.1 PPM for (a), 10 PPB for (b) and (c)
<HC>	(a) Lead to particle formation by photochemical processes (b) Lead to noxious and toxic products	<1 PPB (?) (necessary to distinguish species)
O_3	Irritant and destructive; a product of photochemical processes involving <HC> and NO_x	10 PPB
PAN'S	A class of toxic and irritant products of protochemical processes	1 - 10 PPB
Hg	Atmosphere transports Hg, which is toxic where it accumulates in the biosphere	10^{-2} PPB
HEAT RELEASED	A factor in regional climate change	—

TABLE II

REQUIREMENTS FOR MEASURING POLLUTANTS FOR WHICH CONCERN IS SPECULATIVE OR LONG TERM

CONSTITUENT AND REGION OF THE ATMOSPHERE	GLOBAL	
	PROBLEM: Why are we concerned?	Accuracy
CO TROPOSPHERE AND STRATOSPHERE	(a) Is concentration changing due to man's burning of fossil fuels (b) Determination of destruction processes in the stratosphere	10 PPB
HNO_3 STRATOSPHERE	(a) Determine effect on ozone concentration (b) Does it influence aerosol formation?	1 PPB
>HC< STRATOSPHERE	Do they influence aerosol formation?	Not determined except for CH_4. >HC< have not been detected in the stratosphere
CH_4 *TROPOSPHERE* AND STRATOSPHERE	(a) Participates in photochemical reactions *in the lower atmosphere* (b) What is its influence on stratospheric H_2o (and O_3) distribution?	Troposphere 0.5 PPM Stratosphere (0.2) PPM
FLUORACARBONS TOTAL	(a) Probably accumulating due to man's releases (b) Removal mechanisms unknown	.001 PPB (?)
N_2O STRATOSPHERE	Determine its rate of photodissociation in the stratosphere	50 PPB
CONSTITUENT IN LOWER LAYERS	*REGIONAL*	
	PROBLEM: Why are we concerned?	Accuracy
CO	(a) Determination of sources, sinks, and lifetime in lower atmosphere (b) Participates in photochemical reactions (c) Indicative of oceanic processes	10 PPB
H_2CO	(a) Participates in photochemical reactions (b) Irritant at concentration near 1 PPM	1 PPB
HALOGENS	(a) Toxic and damaging (especially fluorine and HF) (b) Bromine is indicative of bioproductivity of the oceans	1 PPB
NH_3	Combines with sulfuric acid to form $(NH_4)_2SO_4$ particles	10 PPB

as SO_2, NO_2, petroleum derived hydrocarbons, etc., are largely confined to the mixing layer in the lower kilometer. Some gases such as ozone fall under both headings.

Space and time resolution is often implied by the problem, but space and time measurement requirements are not given in the tables. It was generally held that to study regional problems ground resolution of the order of 100 square kilometers would be desirable. In the section following, we compare requirements with estimates of measurement capabilities.

MEASUREMENT TECHNIQUES

SPECTRAL REGIONS USEFUL FOR REMOTE SENSING

The primary criterion in selection of a spectral region for use in remote sensing is that the pollutant molecule exhibit some distinguishing spectral signature in that region. Usually, the signature arises due to molecular absorption in passive remote sensing systems, but in an active system the signature may also arise due to scattering process as in the laser Raman technique to be discussed later. Thus, choice of a given spectral interval will be strongly dictated by the presence of a measurable molecular absorption coefficient in the interval or by the existence of a sensible spectrally dependent molecular scattering coefficient in the region. Other factors which should be considered are (1) the difficulties in data interpretation, which vary significantly throughout the range from the ultraviolet to the microwave, and (2) the availability and sensitivity of instruments and detectors in the different regions.

In the ultraviolet region of the spectrum, absorption of radiation is accompanied by electronic transitions in molecules. Associated with these changes are vibrational and rotational transitions which in a few cases produce a characteristic structure in the bands. The larger molecules do not have ultraviolet band structure at atmospheric pressure and therefore the applicability of the ultraviolet in pollution monitoring by absorption spectroscopy is limited. A comprehensive tabulation of ultraviolet absorption cross sections for some of the pollutants is included in the report by Sullivan and Holland (1966). The only pollutants having significant absorption coefficients at wavelengths less than 1 μm, in the range transmitted by the atmosphere, are SO_2, NO_2, and O_3 (Ludwig et al., 1969). If laser Raman techniques can be developed for pollution measurement, the ultraviolet region may become of greater importance since the intensity of Raman scattering increases as the fourth power of the radiation frequency. Aside from these limitations, the ultraviolet region is plagued with analytical complexities caused by the importance of Rayleigh and Mie scattering at these short wavelengths. Rayleigh scattering from the gas molecules and Mie scattering from the aerosol and clouds must be separated from the signature being observed, either by computation, using a knowledge of particle size concentration and distribution, or by some measurement technique capable of discriminating between continuous scatter and signature. In general, it is hardly ever practical to compute the effects because the required data are seldom available, and the process is enormously complicated even where the data are available. In some cases discrimination is possible and can be used to make satisfactory observations in the presence of significant interference.

The visible region of the spectrum contains very few molecular absorption or emission bands. The only colored gas that is a common pollutant is NO_2, the gas that causes the so-called brown smog.

The infrared from 2 μm to 20 μm appears to be well suited for remote sensing since virtually every pollutant has an absorption (and emission) band within the region. This spectral range is sometimes called the "fingerprint" region of the infrared and it is used extensively in chemical analysis. In general, absorption bands of different molecules differ widely as to shape, location, and intensity. Table A6 in the report by Ludwig et al. (1969) shows the wavelength positions and low-resolution absorption coefficients for bands of various pollutants. Relatively little work has been done to determine the fundamental absorption properties of pollutant molecules, that is, absorption line strength and half-width, using high-resolution data. The most extensively studied molecules are carbon monoxide (Kunde, 1967), carbon dioxide (Drayson and Young, 1966), ozone (Clough and

Kneizys, 1965), water (Benedict and Calfee, 1967), and methane (Kyle, 1968). In addition, Calfee (National Oceanic and Atmospheric Administration, Wave Propagation Laboratory, Boulder, Colorado) has work under way to determine line parameters for SO_2, and Toth and Margolis (Jet Propulsion Laboratory, Pasadena, California) have similar work under way for SO_2 and other pollutants.

The sources of energy used for passive remote sensing in the 2-20 μm range are the sun and thermal emission by the atmosphere and earth surface. This spectral range includes regions where the sources are purely solar and where they are purely thermal as well as a range where both sources contribute. Whenever thermal energy is present, measurements can be made on both the day and the night sides of the planet. However, in order to interpret these measurements properly, the earth surface temperature and the atmospheric temperature profile must be known. Thus an independent knowledge of these temperatures is required. Such information could be obtained routinely using the SIRS and IRIS type satellite instruments (Wark, 1970; Conrath et al., 1970).

As in the ultraviolet region, the presence of clouds in the instrument field of view will alter the received signal, so they must be considered in data analysis. Although Rayleigh scattering is unimportant in the infrared region, aerosol scattering may cause some measurable effect. In addition, aerosols may absorb and emit enough energy to affect the signal (Kattawar and Plass, 1971; Eddy and MacQueen, 1969). Thus, knowledge of aerosol concentration and characteristics may be required in data analysis.

The far infrared from 25 to 500 μm does not appear to be useful for pollutant sensing, at least in the troposphere, because the rotational bands of water vapor are so intense that they blank out the spectrum. This spectral region may be useful, however, in studying lower stratospheric pollution, since water vapor concentration is one to two orders of magnitude less than in the troposphere.

The microwave region of the electromagnetic spectrum from 10 to 400 GHz (3 to 0.075 cm) is attractive for remote sensing applications. The source of energy is emission by the earth and atmosphere. As in the infrared region, measurements of energy can be made during both the day and the night. Several advantages exist in this spectral range as compared to the infrared. The earth surface emissivity is lower by about 50 percent than in the infrared so that surface radiation adds less interfering background to the intensity of upwelling radiation. Also, the atmosphere has windows where transmission of microwave radiation is high, even in the presence of clouds (Ludwig et al., 1969). This is a significant advantage since clouds present a formidable analytical problem in the ultraviolet and infrared regions. According to Ludwig et al. (1969), the microwave region has a severe disadvantage in that spectral lines are very broad in the troposphere. If this is true, it would not be possible to resolve the fine structure characteristic of a given molecule, as is usually necessary in order to distinguish between molecules. This suggests that measurements would have to be limited to the upper troposphere and stratosphere where pressures are low enough to allow unambiguous identification of a given species. William F. White of the Langley Research Center, on the other hand, suggests that the spectral line half-widths quoted by Ludwig et al. (1969), for ammonia gas as an example, may be too high by a factor of about 14. Preliminary results of experiments by White indicate that the air-broadened half-width for all pollutants is of the order of 4 megahertz per millimeter (of mercury) pressure. Thus, even though overlap of spectral lines could be a problem in the troposphere, the problem may not be as severe as is presently indicated. In any case, this question should be re-examined. Unfortunately, very little absorption data exists for pollutant molecules in the microwave region, and work should be undertaken to fill this void. Absorption data presented by Ludwig et al. (1969) are shown in Figure 2. Even if line broadening is a problem in the troposphere, it should be possible to use microwave measurements in the upper atmosphere where pressures are much lower. It appears that it will be difficult to obtain data with high spatial resolution using microwave sensors because of the constraints on the sizes of antennas that can be carried on unmanned satellites. According to Alishouse et al. (1971), a 19-meter antenna is needed at 19 GHz to achieve 1-km resolution using a satellite instrument in a 1000-km orbit.

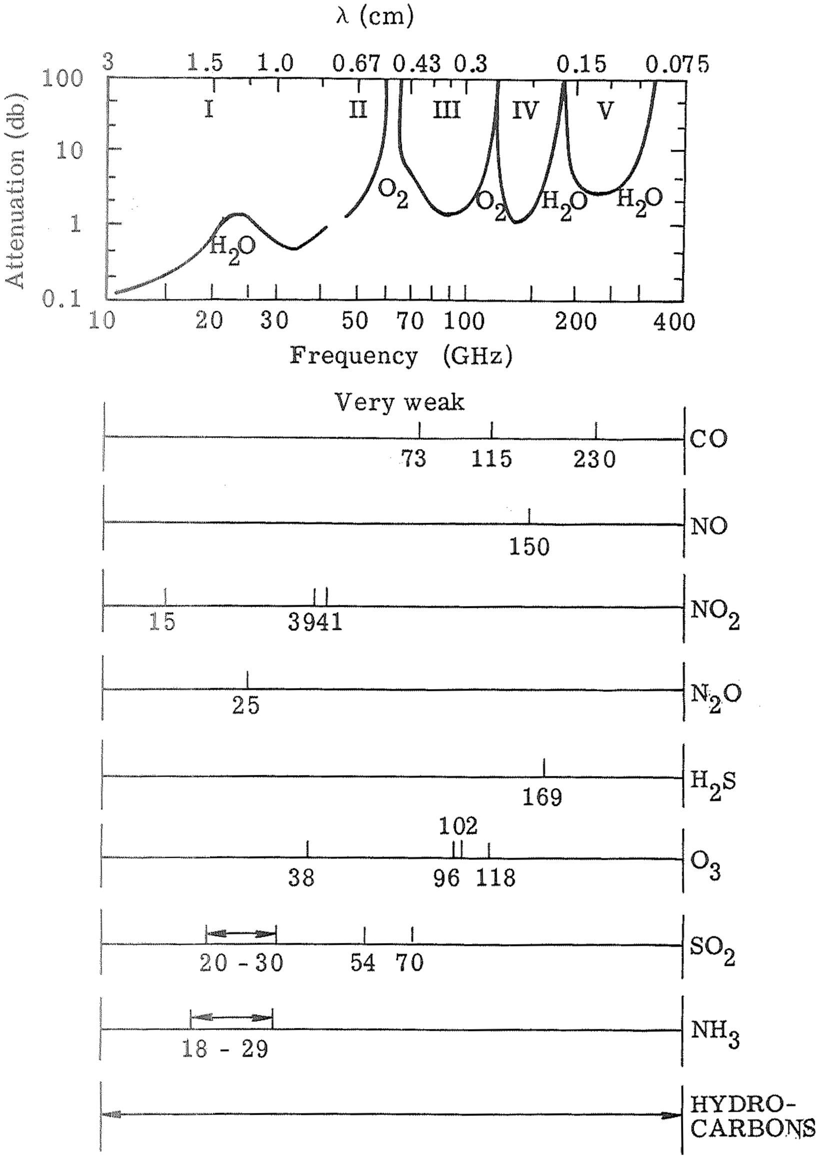

Figure 2.—Atmospheric transmission windows in the microwave region and air pollutant absorption frequencies.

(Ludwig et al., 1969)

The required diameter for a given spatial resolution decreases with both orbital altitude and wavelength. For example, at 100 GHz frequency, where several pollutants have absorption bands, the required diameter to achieve 1-km resolution is only 1.6 m for an orbital altitude of 500 km. Other factors that have impeded the progress of microwave sensors in remote sensing are cost and accuracy (Ludwig et al., 1969).

MEASUREMENT APPROACHES

LIMB MEASUREMENTS

Limb Emission

In the limb-emission approach, the instrument is pointed toward the planetary limb, or horizon, and scanned in the vertical, allowing measurements of vertical profiles. Thermally emitted energy or scattered solar energy from a narrow region of the atmosphere is measured.

There are several advantages to this approach (Gille and House, 1971):

High vertical resolution—The geometry of the limb experiment is such that most of the energy originates from a vertically thin region (about 2-3 km for thermal radiation) located close to the tangent point in the atmosphere, which is the point where the line of sight of the instrument intersects the radius vector of the earth perpendicularly. This allows many independent pieces of information to be obtained concerning the inferred constituent.

Sensitivity—The long slant path through the atmosphere contains 60-100 times more of the constituent of interest than a vertical path down to the tangent point, thereby providing increased sensitivity to gases present in very small amounts.

Background—The signal is seen against the cold black background of space, so that ambiguities of interpretation due to variations and uncertainties in the background surface characteristics do not occur, as they can for the nadir viewing case.

Coverage—When thermal radiation is being measured, determinations may be made in all parts of the orbit, and global coverage is possible from a polar orbiter. Scattered solar radiation may only be measured on the day side, of course.

The geometry also imposes certain disadvantages. The presence of clouds along the ray path disrupts the measurements, so that determinations on a routine basis may be expected only in and above the upper troposphere. Constituent concentrations will be horizontally averaged over 200 km along the ray path; the corresponding ambiguity should be relatively small, however, as most variations in the stratosphere have large horizontal length scales. As with all thermal techniques, the temperature profile must also be known in order to accurately interpret the measurements of constituent emission.

Most studies of the limb approach have considered only infrared energy (e.g., Gille, 1968b; McKee et al., 1969; House and Ohring, 1969; Gille and House, 1971; Russell and Drayson, 1972) although some work has been done using the ultraviolet spectrum (Newell and Gray of Massachusetts Institute of Technology). A limb-emission experiment using the infrared to measure temperature, ozone, and water vapor in the stratosphere with a 4-channel radiometer has been accepted for the Nimbus F satellite, now scheduled for a 1974 launch. In addition, the experiment referred to in the earlier discussion of nitric acid is a similar but advanced experiment to measure the same three parameters in the lower stratosphere and also to measure some pollutants.

It should be noted that many of the balloon experiments performed by the University of Denver (e.g. Murcray et al., 1969) are essentially limb-emission experiments from within the atmosphere. It should also be possible to apply the limb-emission approach to measure pollutants by using an aircraft in the troposphere. Measurement would then be possible only on clear days, or else they would be limited to altitudes above the clouds.

Limb Absorption

The limb-absorption technique, sometimes referred to as the occultation technique, also allows one to determine the vertical profile of an atmospheric gas or pollutant. It consists of measuring the attenuation of solar radiation by the gas as the radiation passes horizontally through the atmosphere. The moon or a stellar source can also be used as the source of radiation. The measuring platform may be either a balloon or a satellite.

In the case of the balloon platform good vertical resolution of the constituent being measured can only be realized up to the altitude of the balloon. While good vertical resolution (of the order of 1 km) up to extremely high altitude can be achieved from a satellite platform, the resolution is limited unless high pointing accuracy is available so that the instrument receives a narrow beam from only a small portion of the solar disk. For example, the projected diameter of the sun in the earth's atmosphere seen from a satellite with a 500-km orbit is larger than 20 km. In order to achieve fine resolution in the vertical, the effect of refraction must be carefully considered.

If clouds are present, this method can only be used down to the altitude of the top of the clouds. When the atmosphere is free of clouds, limb-absorption methods can be used to remotely measure constituents down to the ground. The resolution that can be achieved in the lower atmosphere is not as high as in the upper atmosphere, because of larger refraction effects.

Since vertical soundings can be made using limb-absorption only during sunset or sunrise, it is desirable to make this type of measurement from a satellite in an orbit that offers a large number of satellite days. The method is restricted to those latitudinal regions where proper sun alinement exists for a given orbit.

The limb-absorption method has been used previously from balloons to determine stratospheric constituents (Murcray et al., 1969; Pepin, 1969), and the general approach has been used to measure ozone and molecular oxygen from satellites (Frith, 1961; Rawcliffe, 1963; Miller, 1969; Hays and Roble, 1972). It has been described in some detail by Duardo (1967).

An experiment using this method is planned for the OSO-J satellite scheduled for launch in 1974. This experiment, called Wyoming SAM (Stratospheric Aerosol Monitor), will determine the aerosols and ozone in the stratosphere with a vertical resolution of the order of 1 km, from the equator to the middle latitudes.

Active Source

In this system, at least two or more cooperating satellites are required, one providing the light source and the other housing the receiver or a retro-reflector. The pollutant could then be observed in absorption. While this approach is theoretically very advantageous, the practical problem of alining source and receiver make it unattractive. However, the approach may be more practical with manned space stations. The use of lasers as light sources is a possibility, and the development of powerful and stable lasers for space application should be encouraged.

VERTICAL MEASUREMENTS

Thermal Emission

Between approximately 4 μm and 5 μm, the upwelling radiation from the earth's surface and atmosphere equals that of the reflected sunlight, while at the longer wavelengths, the thermal emission is much more intense than the reflected sunlight. Thus, the spectral region starting at about 3.5 μm and extending up to the microwaves is called the "thermal emission region". During daytime, the reflected sunlight must be taken into account up to about 6 μm. Thus, both energy sources have to be considered when daytime observations are made between about 3.5 and 6 μm.

All pollutants have absorption bands in the thermal emission region, some of them exclusively so. Some pollutants, including CO_2, SO_2, NO_2, and CH_4, also have bands in the lower wavelength region, where reflected sunlight dominates.

The spectral signature of a pollutant having sufficient optical thickness will be observable in a spectrum taken by a satellite instrument with sufficient spectral resolution. This is important for the purpose of identification. However, additional information is needed in order to determine quantitatively the vertical burden and especially to determine the vertical distribution. For the quantitative determination of the vertical burden, the ground brightness temperature and the atmospheric temperature profile must be known and, in addition, an assumption about the vertical distribution of the pollutant must be made. The required knowledge of the ground and atmospheric temperatures can be provided by already developed instrumentation. Assumptions about the vertical pollutant distribution can reasonably be made, based upon past measurements. However, the availability and accuracy of additional temperature measurements and the validity of the assumed vertical pollutant distribution will influence the accuracy with which the vertical burden can be determined.

At the present time, it seems unlikely that the vertical distribution of pollutants can be determined remotely. However, in cases where a pollutant can be observed simultaneously in the reflected sunlight and thermal emission regions, or in the case of cloud cover, when the cloud top height is known, an approximate vertical distribution may be inferred.

Absorption Techniques with Reflected Solar Radiation

Measurements of the absorption spectra of gases can be made from spacecraft in a downward looking mode using the sun as a source of radiation. Such measurements can be related to the total burden of gases within the atmosphere; that is, they do not measure concentration directly but rather the integrated mass in a vertical column. However, approximate concentration levels can be deduced if complementary information is available from other sources which provides data concerning such things as meteorological conditions, temperature profiles, and pollutant concentrations at ground level.

Spectral regions for absorption techniques applicable to remote probing of the troposphere from a satellite lie in the ultraviolet, visible, and infrared, between 0.3 and 4 μm. In the visible region, and especially in the ultraviolet region, a considerable portion of the light seen at the spacecraft is backscattered radiation that has not reached the ground.

Uncorrected measurements of absorption spectra present in this radiation would therefore not present the effects of the total vertical burden of gas. However, the fluctuating albedo of the earth's surface as seen with a telescope having high resolution optics and scanning the surface of the earth, may provide a way to distinguish between a component of the light that has been reflected from the earth and the unmodulated radiation backscattered by the atmosphere. Experimental balloon and aircraft flights measuring SO_2 and NO_2 in the ultraviolet and visible regions respectively have tended to support the feasibility of identifying these gases from space (Barringer, 1970). Current airborne tests of the fluctuating albedo technique indicate this to be a promising approach to the backscatter problem in the ultraviolet and visible regions and a means of improving the quantitative reliability of measurements of vertical burden in these spectral regions.

The presence of cloud cover prevents measurements beneath the cloud so that inevitable holes in the data must occur with any satellite system using these techniques. However some advantage can be taken of cloud cover in obtaining information on the high-altitude distribution of gases. Complementary information is required, however, on cloud height and distribution, both of which can be obtained by other remote sensing techniques which could be used on the same satellite.

The spatial resolution of data obtained from downward looking absorption techniques is a function of the resolution and angular acceptance of the optics employed. Some compromise is required between the conflicting requirements of high spatial resolution and high measurement sensitivity, since the signal-to-noise ratio is a function of angular resolution, scanning rate, size of optics, etc. In general, however, a scanning system that provides some form of two-dimensional map of the gas distribution over the earth's surface is considerably more useful than a system that gives only a series of line profiles along the track of the satellite. Such a scanning system, even if it is unable to acquire any resolved information such as the vertical distribution can nevertheless provide valuable data on the mass movement, migration, and dispersion of pollutant gases laterally over the surface of the earth.

Instruments suitable for the measurement of absorption spectra in the downward looking mode from satellites include optical correlation instruments of both the dispersive and non-dispersive type. In some cases filter-wheel radiometers and spectrometers may be applicable although this possibility is questionable due to the high noise levels associated with the use of the changing earth's surface as a background. Similar problems arise in applying scanning spectrometers.

Absorption Techniques with Active Sources

Some possibility exists that downward looking absorption measurements could be made using tunable lasers that can rapidly scan one or more absorption lines of a pollutant gas. In this case the earth would be used as a reflector and differential absorption would be measured during rapid scanning. However, at the current state of the art, such techniques are not as practical as passive methods.

Stimulated Emission with Natural Sources

The Fraunhofer line discrimination technique (Hemphill et al., 1969) can be used for identifying luminescent phenomena by remote sensing in daylight. It depends upon the precision measurement of the depth of Fraunhofer absorption lines in the solar spectrum and the apparent changes in the depth of these lines when they are reflected from the earth. The ratio of energy at the edge of a Fraunhofer line to the energy at the center will remain unchanged if the light is reflected from a nonluminescent surface, but if there is a contribution of luminescence from the surface, within the wavelength region of the Fraunhofer line, the ratio will be changed.

Equipment has been constructed and flown employing narrow band Fabry-Perot optical filters having a band width of 0.07 nm and using a method of referencing against the sun, so that the effects of solar activity in causing rapid temporal changes in the Fraunhofer line depth can be normalized out.

The principal application of the technique has been for the detection of Rhodamine B tracer dyes in water for hydrological purposes, but chemiluminescent effects in smog over New York City have also been observed by this technique. The correlation of this type of luminescence with the buildup of oxidant pollutants could prove to be a useful experiment.

Stimulated Emission with Lasers

Laser technology has not as yet been used for detecting gaseous pollutants from a satellite; however, a number of ground observations indicate that this method shows promise. The proposed laser system would be single-ended using a satellite-based laser, and would require observation of backscattered laser energy. The advantage of active systems is that they do not depend on the available radiation from either the earth or sun. In fact the solar energy, which is superimposed, is the noise on the examined signal. This noise can be eliminated by laser pulsing. A controlled laser source would have the advantage of obtaining a vertical profile of the pollutant with a resolution limited only by the relaxation time of the physical interaction examined.

The backscattered energy is dependent upon four principal interactions with the atmosphere: Rayleigh scattering, Mie scattering, resonance scattering, and Raman scattering. Rayleigh and Mie scattering cannot be used for identifying gaseous pollutants. (Mie scattering can be used for dust and aerosol detection.) In resonance scattering the wavelength of the laser pulse falls on the center of the resonant line of the pollutant, that is, at a line which is produced by an allowable transition from an excited to the ground state of the gas. In Raman scattering the wavelength of the scattered energy is different from that of the incident energy. The shift is dependent upon the scattering gas and is a unique signature of the gas. Although the scattering intensities are much smaller (10^{-3} to 10^{-5}) than in resonance scattering, the Raman technique has several advantages: (1) unique signature of pollutants, (2) elimination of the requirement for exact matching of laser and pollutant lines.

and (3) multipollutant detection with one laser (Hanst, 1970).

INSTRUMENTS

In the preceding section, we have reviewed the modes of observation by which measurements of gaseous pollutants can be made. Before proceeding to the descriptive summaries of the principal classes of instruments that can be used, it is necessary to discriminate between two types of measurements, distinguished by their objectives, as these strongly influence the choice of instrumentation appropriate to a given problem. These are "survey" and "specific" measurements. In the first of these, the objective is to identify which molecular species are present; the instrumentation must be capable of detecting and identifying unambiguously the trace molecular constituents as a function of location. The second, the specific observations, have as their objective the measurement of abundance and abundance variations of particular pre-selected pollutant species. In terms of the application of systems that are designed for optimum efficiency and information content, these two different types of measurements impose very different requirements on the performance specifications of the instrumentation to be used.

A number of instrumentation techniques have been suggested for the remote measurement of pollution. In all these methods, the main instrument strategy has been to achieve both high spectral resolution and high signal-to-noise ratios, in order to distinguish between overlapping spectra of different molecules. This sorting out of overlapping spectra is not a trivial task, since the concentrations of natural gases are orders of magnitude greater than the pollutant concentrations. Various methods of achieving high resolution have been proposed, but generally these may be described as (1) simply high resolution instruments or (2) correlation instruments. The former approach utilizes basic high resolution spectrometers and interferometers. The main strategy of the correlation approach is to use prior knowledge of a given spectral signature of a pollutant in order to detect its presence among many other gases. This signature is stored within the instrument by various means—such as with a matched filter, gas filter, magnetic drum, or electronic storage. Comparisons are made between the stored signature and the input energy within a given spectral band. It is possible, in effect, to eliminate the background signal by using this technique and retain a signal only at the correlation points. These techniques and others are described in the following paragraphs.

RADIOMETERS

A radiometer measures the intensity of electromagnetic radiation within a given spectral interval. Radiometers can be divided into two classes by differentiating the two basic means of obtaining spectral intervals—filter techniques and dispersive techniques.

The simplest filter system consists of one set of optics, one optical filter, and one detector. In a multichannel-filter radiometer each filter has its own optical elements and detector; it is an elementary form of spectrometer. A five-channel instrument of this type has been flown on Nimbus satellites and has been used to measure ozone and water vapor concentrations (Nimbus III Users Guide, 1969). An alternative technique utilizes a single-channel radiometer and filters that are sequentially inserted into the system. The sequencing can be accomplished with a rotating wheel containing fixed filters. A filter wheel radiometer has been developed for a ground-based measurement of O_3 with a 1.6 km path length and a sensitivity of 0.1 ppm (Prostak et al., 1970). The filter wheel technique reduces the number of detectors and sets of optics to one each, but at the expense of greater sampling time and an added mechanical subsystem.

A polychromator radiometer utilizes a dispersing element and a detector array at the exit plane of the spectrometer. All channels are observed simultaneously, as with the multichannel-filter radiometer. The multiplexing property of the polychromator radiometer leads to a higher signal-to-noise ratio in remote sensing applications than is available with the filter techniques, but a penalty is paid in instrument complexity and weight. This type of instrument has been flown on Tiros and Nimbus as "Satellite Infrared Spectrometer (SIRS)" to obtain temperature and humidity profiles (Wark et al., 1970).

Microwave radiometers differ from the ultraviolet, visible, and infrared types. The optics of the latter types is replaced by an antenna and the optical filters are replaced by tuned circuits. Ground-based measurements of water vapor have been made with a microwave radiometer (Toong et al., 1970).

SPECTROMETERS

Under this heading are included spectrally dispersive instruments whose output is the continuous variation of intensity with wavelengths. Three types of spectrometer are considered: the conventional prism or grating instrument, the filter wedge (a continuously variable interference filter), and a comparatively recent development, the derivative spectrometer.

The conventional scanning spectrometer has to a large extent been replaced during the past few years by more sophisticated systems of the multiplexing and correlation types, which offer advantages in terms of efficiency or information gathering capability. Such advantages are particularly important in situations where the available energy and time of observation are limited. However, the spectrometer in its conventional form still finds application where high resolution and flexibility are desired and energy is not restricted (as with the grating spectrometer) or where a modest required resolution allows a comparatively low-cost advantage to be exploited (as with the filter wedge).

Examples of space applications of grating spectrometers are the ultraviolet instruments of Barth et al. (1971) and the near-infrared instrument of Farmer et al. (1971). The filter wedge, while not capable of achieving the spectral resolution of grating or prism instruments (its maximum resolving power is about of the order of 100), has the advantage of optical simplicity and economy. Instruments that have recently flown include the infrared systems developed by Hovis (1967) and by Herr and Pimentel (1969).

The derivative spectrometer, in essence, produces a differentiated output over a small spectral interval (Stauffer et al., 1968). This technique enhances the detectability of weak blended spectral features and also provides suppression of background spectral characteristics and their variations.

Subtle inflections which are unique to a pollutant spectral signature are brought out by this technique. An instrument for the measurement of SO_2, NO_2, O_3, and NH_3 is currently under development (Williams et al., 1969).

INTERFEROMETERS

The Michelson interferometer is a versatile multiplexing instrument; it can deliver as much spectral information as a conventional grating spectrometer of similar dimensions, in a very much shorter period of time. This gain in speed results from its high throughput (energy grasp) coupled with the advantage of complete multiplexing.

The resolving power of the Michelson interferometer depends upon the distance of travel of the movable reflector. The spectral resolution is the same at all frequencies within the range of a given instrument (and is equal to the reciprocal of twice the traverse distance). This feature is of particular relevance in the detection of trace species at low concentrations in the troposphere; at tropospheric pressures the individual rotational lines, in the active bands of all of the molecules and radicals which are of concern, have closely similar half-widths (0.05 to 0.1 cm^{-1}).

The high spectral resolution required for most global and regional remote sensing observations of gaseous pollutants demands a high system stability. This can be achieved by modifying the simple Michelson interferometer by replacing the plane mirrors in the interferometer arms with retroreflectors. This modification eliminates sensitivity to angular displacement. The effect of lateral displacements is overcome by double-passing through the optical system (Beer, 1967).

Hanel and his co-workers (for example, Hanel, 1971) have developed Michelson interferometers for space applications covering the 6- to 40-μm wavelength range having spectral resolutions of a few cm^{-1} down to a cm^{-1}. These instruments, operating in the thermal emission region, have produced vertical temperature and water vapor profiles on a global scale.

A high-speed incrementally stepped interferometer, having a resolution of 0.15 cm^{-1} and covering the reflected solar energy region of the near infrared spectrum (1-5 μm), has been described by Schindler (1970). This instrument has been developed primarily for operation in the survey mode; that is, it is intended for global identification and measurement of pollutant species, as opposed to mapping of specific molecules.

OPTICAL CORRELATION INSTRUMENTS

Dispersive Type

Optical correlation instruments are characterized by the use of matched filtering techniques in which real time identification of a gas absorption or emission spectrum is carried out by correlation against a stored reference. There are two broad classes of dispersive instruments, one of which gives spatially dispersed information, and the other time dispersed information.

In a typical instrument of the spatially dispersed type, a spectrum of the incoming radiation is dispersed by a grating onto a mask in the exit plane of the spectrometer, the mask carrying a number of slits corresponding to the principal absorption bands of the gas. (Barringer and Schock, 1966; Strong, 1967; Williams and Kobitz, 1968). The spectrum is caused to oscillate on the mask and, as a result, the periodically fluctuating signal that passes through the mask is coherently detected in synchronism with the applied oscillation frequency. High sensitivity is achieved by virtue of the large light throughput obtained in comparison with a conventional spectrometer having a single exit slit, and also by the use of synchronous detection techniques in the electronics. For regularly banded spectra such as that of sulfur dioxide in the ultraviolet, considerable additional sensitivity can be achieved by the use of multiple entrance slits.

More recent versions of the correlation spectrometer have employed masks introduced sequentially on a rotating disc in order to provide alternate correlation with absorption peaks and absorption minima. This technique is more sensitive and has a higher interference rejection for irregular spectra.

A typical time dispersive correlation instrument is the correlation interferometer (Dick et al. 1971). This is basically a Michelson interferometer in which interferometric scanning of incoming radiation is carried out and real-time matching is employed against stored interferograms of the gas being detected. In practice, selected portions of the interferometer and the correlation reference is attached to or synchronized with the rotation of the compensation plate.

In time dispersive correlation a finite time is required to carry out a scan, and when the source signal is fluctuating in intensity, means must be provided for minimizing noise that this introduces into the measurement. In the case of earth oriented instrumentation aimed at the earth's surface, this can be achieved by image motion compensation provided that the scan time duration calls for a shift of not more than a few degrees of the viewing incidence angle by the image motion compensator (typically a scan time of not more than one or two seconds).

Another example of dispersive optical correlation is the so-called Hadamard-Transform spectrometer, which received its name from the fact that the mathematics of this new concept is related to Hadamard matrices. A series of masks is placed at the exit (or entrance) slit of a conventional dispersion spectrometer. For each mask, a different combination of spectral elements falls on the detector. Intensities measured with m different masks can be used to compute the intensities of m different spectral bands. The m measurements yield m linearly independent equations, which are solved simultaneously to yield the m intensities. If the measurements are chosen properly, an advantage similar to the multiplex advantage of interferometers can be obtained (Nelson and Fredman, 1970). A practical application to the analysis of automobile exhaust is being proposed by Decker (1971).

Non-Dispersive Type

As the name implies, this class of correlation instruments does not use a dispersive element to divide the incoming energy into discrete wavelength intervals. It uses the pollutant gas for which the measurement is being conducted as its own filter. Utilizing the rotational fine structure as the filter function, the spectral signature of the incoming radiation is correlated against the signature of a pollutant gas in a sample cell. By using an additional (evacuated) cell as reference and differencing the signals from the two cells, a set of differently distributed spectral lines of an interfering gas and/or continuum radiation is not detected. The nondispersive optical correlation instrument combines the advantages of large throughput (because no entrance slit is used) and multiplexing (because all spectral elements are seen simultaneously) with relative simplicity. The first instrument of this type, using a microphonic detector, was described by Pfund (1939). It is now being used as an *in-situ* monitor for pollutant gases. A further development was reported by Goody (1968). Recently, a modified version called the "Selective Chopper Radiometer," has been used in the remote sounding of atmospheric temperature profiles from satellites (Houghton and Smith, 1970). Another version, called the "Gas Filter Correlation" instrument, was developed for the *in-situ* monitoring of toxic gases in the ppb range (Bartle et al., 1971) and for the remote detection of CO from aircraft (Ludwig et al., 1971). A development for satellite application is under way utilizing several cell pairs for multiple pollutant detection.

The limitation of the instrument lies in the fact that the condition of the pollutant gas in the cell (pressure and temperature) should be similar to the conditions under which the pollutant in the atmosphere exists. Thus, for satellite applications in which tropospheric and/or stratospheric distributed pollutants are to be measured, the varying conditions may be approached by using several cells with different pressures or by using pressure modulation of one cell.

LASERS

One limitation of the previously discussed techniques is that they are passive and are limited by the amount of input energy. Active methods of remote sensing can call on the high intensities available from lasers. The ability to collimate the high intensity light source and the very narrow spectral line widths makes the laser very attractive for pollution measurements. Narrow line widths mean, however, that laser lines must be found that fall on absorption lines of the pollutants. There are a number of techniques (Hanst, 1970; Menzies, 1971) available for shifting the frequencies of gas lasers to some degree. These methods include the use of pressure and temperature control, mirror position control, and magnetic field control. Tunable crystal lasers for infrared use include the semi-conductor lasers, the Raman spin-flip laser system, and the optical parametric oscillator laser system. The principal limitation of the active method for observing infrared absorption is that on reflection from natural targets the laser beam loses its collimation. This collimation is preserved, however, if the beam is reflected from corner reflectors, such as the ones left on the moon. For scattering experiments operating in the visible and ultraviolet, pulsed crystal lasers and tunable dye lasers are used.

Raman scattering experiments have been successful using frequency doubling ruby lasers. Measurements of H_2O from 0-3 km with an accuracy of parts per thousand have been performed by Melfi et al. (1969) and Cooney (1968). SO_2 and CO in plumes at a distance of 20 meters were measured by Koboyasi and Inaba (1970). Using resonance Raman scattering produced by a tunable dye laser, Bowman et al. (1969) measured sodium at a range of 85 km. This particular experiment shows that low density measurement is possible from satellite distances.

There is little doubt that a place has been set for laser techniques in the pollution field. However, resonance and Raman scattering methods have not yet been proved to be sufficiently sensitive to allow remote measurement of the ambient pollution by airborne or spaceborne laser systems.

MEASUREMENT CAPABILITIES

Table III summarizes findings of the Gaseous Air Pollution Panel concerning present measurement capabilities. Column 1 lists the gases in the approximate order of the need for their observation as described in Tables I and II. Column 2 indicates the height range of the measurements, which was restricted for this study to levels between the stratopause (about 50 km) and the surface. The third column

TABLE III

MEASUREMENT CAPABILITIES FOR REMOTE SENSING OF TRACE GASES

CONSTITUENT	ALTITUDE RANGE OF MEASUREMENT	ALTITUDE RESOLUTION	CAPABILITY	MEASUREMENT APPROACH
CO_2	ENTIRE	TOTAL	POTENTIALLY FEASIBLE	II.2 - SOLAR IR. Required accuracy will be very difficult to obtain.
$(C^{13}O_2/C^{12}O_2)$	ENTIRE	TOTAL	FEASIBLE	II.2 - SOLAR IR. Not required *measurement, but may be useful in* distinguishing between sources.
CO	TROPOSPHERE	TOTAL	FEASIBLE	II.1 and II.2. - SOLAR IR and THERMAL IR
SO_2	TROPOSPHERE	TOTAL	DEMONSTRATED IN TESTS-REGIONAL POTENTIALLY FEASIBLE-GLOBAL	II.2. - SOLAR UV. Demonstrated from a balloon, using correlation spectrometer
			FEASIBLE-REGIONAL POTENTIALLY FEASIBLE-GLOBAL	II.1 - THERMAL IR
			FEASIBLE-REGIONAL POTENTIALLY FEASIBLE-GLOBAL	II.2 - SOLAR IR
	STRATOSPHERE	FEW km	POTENTIALLY FEASIBLE	I.2 - SOLAR IR AND THERMAL IR
		FEW km	POTENTIALLY FEASIBLE	*I.1 - THERMAL IR*
O_3	STRATOSPHERE	2 km	FEASIBLE	I.1 - THERMAL IR. Under development for NIMBUS F.
		0.5 km	DEMONSTRATED IN TESTS	I.2 - SOLAR visible. Demonstrated on balloon. Under development for OSO-J.
		TOTAL	DEMONSTRATED IN TESTS	II.2a. - SOLAR UV. Flown on Nimbus 4. Accuracy of $<10\%$ achieved. Method can also give height distribution above O_3 maximum
	HIGH STRATOSPHERE AND MESOSPHERE	1 km (?)	DEMONSTRATED IN TESTS	I.2 - STELLAR UV. Results have been obtained using OAO data for altitude range - 40 km to 90 km.
	ENTIRE	TOTAL	*DEMONSTRATED* IN TESTS	II.1 - THERMAL IR. Flown on Nimbus 3 and 4. Accuracy - 5% achieved.
H_2O	TROPOSPHERE	?	DEMONSTRATED IN TESTS	II.1 - THERMAL IR. Flown on Nimbus 3 and 4. Does not meet accuracy requirement measurement in high troposphere difficult.
	STRATOSPHERE	2.5 km	DEMONSTRATED *IN TESTS*	I.1 - THERMAL IR. Flown on rocket but required accuracy not achieved.
		<1 km	DEMONSTRATED IN TESTS	I.2 - SOLAR IR. Flown on a rocket. Potentially can extend to mesosphere.

TABLE III—(continued)

MEASUREMENT CAPABILITIES FOR REMOTE SENSING OF TRACE GASES

CONSTITUENT	ALTITUDE RANGE OF MEASUREMENT	ALTITUDE RESOLUTION	CAPABILITY	MEASUREMENT APPROACH
NO_2	TROPOSPHERE	TOTAL	DEMONSTRATED IN TESTS	II.2 - SOLAR visible. Demonstrated on a balloon, using a correlation spectrometer
			FEASIBLE	I.2 and II.2 - SOLAR IR & THERMAL IR.
	STRATOSPHERE	FEW km	FEASIBLE	I.2 - SOLAR VISIBLE
			POT. FEASIBLE	I.1 - THERMAL IR
NO	TROPOSPHERE	TOTAL	FEASIBLE	II.1 - THERMAL IR
	STRATOSPHERE	Few km	FEASIBLE	I.2 - THERMAL IR
HC	STRATOSPHERE	Few km	POTENTIALLY FEASIBLE	I.1 or I.2 - If concentrations are in PPB range
CH_4	STRATOSPHERE	Few km	FEASIBLE	I.1 or I.2 - Thermal IR or SOLAR IR
H_2CO	TROPOSPHERE	TOTAL	POTENTIALLY FEASIBLE	II.2 - SOLAR IR and SOLAR UV. Capable of measurements in PPB range but required accuracy not known.
C_2H_2	TROPOSPHERE	TOTAL	POTENTIALLY FEASIBLE	II.2 - SOLAR IR. Capable of measurements in PPB range but required accuracy not know.
C_2H_4	TROPOSPHERE	TOTAL	POTENTIALLY FEASIBLE	II.2 - SOLAR IR. Capable of measurements in PPB range but required accuracy not known
H_2S	TROPOSPHERE	?	NOT CURRENTLY FEASIBLE	?
N_2O	STRATOSPHERE	Few km	FEASIBLE	I.1 or I.2 - SOLAR IR or THERMAL IR
I_2	TROPOSPHERE	TOTAL	DEMONSTRATED IN TESTS	II.2 - SOLAR visible. Demonstrated from an aircraft over marine source
HCl	TROPOSPHERE	TOTAL	FEASIBLE	II.2 - SOLAR IR
HF	TROPOSPHERE	TOTAL	FEASIBLE	II.2 - SOLAR IR
HNO_3	STRATOSPHERE	Few km	DEMONSTRATED IN TESTS	I.1 or I.2 - THERMAL IR or SOLAR IR. Demonstrated in balloon experiment.
NH_3	TROPOSPHERE	TOTAL	FEASIBLE	II.2 - SOLAR IR
	STRATOSPHERE	Few km	FEASIBLE	I.1 or I.2 - THERMAL IR or SOLAR IR.
FLUOROCARBONS	TROPOSPHERE	TOTAL	NOT CURRENTLY FEASIBLE	Detectability not yet determined
Hg	TROPOSPHERE	?	NOT CURRENTLY FEASIBLE	?
HEAT RELEASED	SURFACE	TOTAL		Depends upon ability to measure surface temperature, air temperature change, wind, water vapor, etc., since heat released will take many forms.

is a tabulation of the vertical resolution capability provided by a given measurement approach. The entry "Total" indicates that the measurement approach gives the integrated amount of gas between the ground and the instrument. Column 4 gives a rating of the ability of the measurement approach to provide the required accuracy as specified in Tables I and II. Four rating categories are used:

Demonstrated in tests—A measurement approach has been used in the atmosphere and has given measurements within the required accuracy range.

Feasible—Theoretical studies, or laboratory tests, or both have been completed which indicate that the measurement is possible. Usually, this category implies that the only instrument development required is that necessary to demonstrate the measurement approach in the atmosphere or to make the instrument "flight qualified".

Potentially feasible—A measurement approach exists but its feasibility for measuring a given gas has not yet been determined; or an instrument system exists but its capability to provide the required accuracy is not known.

Not currently feasible—There are no known techniques which can meet the observational requirements either because of spectral interference which masks the absorption band of interest, or because ambient concentrations are below the minimum level of detectability of present instrumentation, or because the gas does not exhibit a strong absorption band in a useable wavelength range.

The last column of Table III describes the measurement approaches for each gas. These methods are discussed in detail in the section entitled "Measurement Approaches" and they are briefly listed again here for reference:

I. Limb
  1. Thermal Emission
  2. Absorption
II. Vertical
  1. Thermal Emission
  2. Absorption

Table III specifies the spectral regions used for measurement, it lists the type of atmospheric demonstration when an approach has been demonstrated in tests, and it includes notation of any special difficulties to be anticipated. In some cases, two ratings were assigned for a given measurement approach and a particular gas, depending upon whether the method would be used for a global measurement or a regional measurement. This was necessary since global background values are generally smaller than regional levels and thus are more difficult to measure. Table III does not include information concerning spatial and temporal sampling characteristics since these details are dictated by individual observational programs according to the needs of such programs.

The information presented in Table III is an encouraging summary of the current state of the art of remote measurement of trace gases. The capability to measure many of the gases that are of concern to us either exists now, or else it can be provided after a reasonable development effort to improve present methods. In many cases, the capability has been demonstrated through measurements made in the atmosphere. The ability to make tropospheric measurements of SO_2, NO_2, and I_2, and to make stratospheric measurements of HNO_3, has been shown through balloon and aircraft tests. Some gases, namely ozone and water vapor, have also been measured from satellites. However, there are some significant deficiencies in our current capabilities. For example, we cannot say that it is feasible to make measurements of the global distributions of important gases such as CO_2, SO_2, and hydrocarbons—these measurements are only potentially feasible; and in some cases, it is not currently feasible to detect certain gases from satellites. These include hydrogen sulfide, mercury, and the fluorocarbons. Also, there are a number of feasible and potentially feasible entries in Table III, further indicating the current early stage of development of remote sensing capabilities. These shortcomings considered in light of the strong need to learn more about the global space and time distribution of trace gases emphasizes the urgency of further research on measurement techniques.

All measurement approaches in Table III are passive methods which use solar radiation or radiation emitted by the earth. Three classes of experiments have emerged in the table: earth oriented, sun oriented, and horizon oriented methods. The former is used to measure tropospheric gases and the latter two experiments are for measurement of gases in the stratosphere. Although it is not specifically noted in Table III, the information contained therein is based on five instrument techniques which have reached an advanced stage of development. These methods hold the most promise for future application in the above experiments. The techniques are radiometry, high resolution interferometry, correlation interferometry, correlation spectrometry, and gas filter correlation.

Radiometry has been used from satellites to measure total ozone concentration and tropospheric water vapor. However in pollution measurement, it is most useful for measurements in the stratosphere, where the problem of spectral absorption band overlap will not be as severe as in the lower atmosphere. It is feasible to use radiometry to measure profiles of stratospheric O_3, H_2O vapor, CH_4, N_2O, NH_3, and HNO_3. It may also be possible to measure SO_2, NO_2, and hydrocarbons.

The remaining four techniques could be used in both the troposphere and stratosphere, but their outstanding advantage—high spectral resolution—makes them especially useful for tropospheric measurements. In theory, these techniques could be used to measure virtually all of the pollutants in Table III that exhibit a measurable spectral signature. However previous work has concentrated on measurement of CO, SO_2, NO_2, and I_2. The greatest use of high resolution interferometric techniques is in qualitative measurements for identification and detection of trace gases. Quantitative measurements are difficult because of image motion compensation problems which arise due to the time required to make a high resolution scan across a given spectral region. Quantitative measurements are more easily obtainable from the correlation techniques.

As Table III illustrates, the five measurement methods do not provide all of the information that is needed. In fact, a highly desirable piece of information—vertical concentration profile in the troposphere—is not provided by any of these techniques in their current stages of development. Such information may require development of other approaches such as active probing. It is hoped that this report provides the stimulus for such research.

RECOMMENDATIONS

In consideration of the conclusions and findings concerning opportunities for remote measurements presented in this report, we recommend that:

1. The distribution of those gases in the stratosphere that play a part in determining the ozone photochemistry and radiative equilibrium be measured concurrently on a global basis from satellites. The primary constituents of interest are O_3 itself, H_2O, NO, NO_2, HNO_3, and CH_4. It is not established that all of these gases can be measured with current techniques; therefore a development program should be undertaken to establish the feasibility of measuring these distributions to the required accuracy.
2. Remote measurement techniques from satellites be exploited to measure regional and global distributions of pollutants in the troposphere, the objective being to establish sources and sinks and to assess the roles of these gases in the environment. Those trace gases that may be measured in this manner to the required accuracy are CO, SO_2, NO_2, NO, and possibly CO_2.
3. Studies be initiated to establish relationships between vertical burden and surface concentrations of trace gases and the results be used in the planning of complementary programs to measure pollutants from the ground and space.
4. Remote measurement techniques be developed and applied to determine vertical concentration profiles of pollutants, and these measurements be used to improve dynamic transport models and to study space and time variations.
5. Research programs be conducted to establish accurate values of the basic absorption properties of pollutant molecules (that is, line strengths, half-widths, and positions) in the infrared and microwave regions of the electromagnetic spectrum.
6. Emphasis be placed on the use of aircraft and balloon platforms in addition to satellites for studying regional pollution problems and in evaluating techniques for eventual use on satellites.
7. Research programs be encouraged to further advance the state of the art beyond the current instrumentation capabilities given in Table III, with particular emphasis on those systems which appear to be potentially feasible.

8. Studies be initiated to assess the potential of microwave techniques for remotely sensing gaseous pollutants.
9. Research programs be established to study the potential of active systems employing lasers for use in remote sensing of gaseous pollutants.

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SECTION III

WATER POLLUTANTS

J. Arvesen
**D. Bowker
G. Clarke
D. Delzell
S. Duntley
*G. Ewing
G. North
A. Park
J. Sherman
P. White
***W. Witte
J. Zeigler

*Chairman of Panel
**Associate Chairman
***Assistant Chairman

SECTION III

WATER POLLUTANTS

INTRODUCTION

Since water plays such a vital role in a biological system, pollution of any part of the earth's water whether salt or fresh is a most important problem indeed. The oceans are the largest segment of the world's total water, since they contain approximately 97.3% of the entire amount. Other segments, while important in the diversity of ecological habitats, are small in comparison. Fresh water lakes, for example, contain about 0.009%, rivers possess 0.00011%, and ground waters constitute approximately 0.61% of the total. Continental water is so small in amount that it is much less than the margin of error in estimates of the oceans and ice caps. Fresh water is relatively much more important than its relative volume, however, because of its domestic, industrial, and agricultural uses. The largest amount of non-ocean water is bound up in the polar ice caps and glaciers. These make up 2.14% of the world's water supply. Consequently, they should be strongly protected against contamination (Nace, 1967).

Water pollution has reached such proportions that some fresh water ecosystems are essentially lifeless or soon will be. For example, the Monongahela River as it empties into the Ohio River is dumping the equivalent of 2×10^8 kilograms of sulfuric acid into that water system per year (Nelson, 1967). In the Pennsylvania coal mine region 5×10^6 cubic meters of acid mine water are discharged daily into the surface drainage (Pollio and Kunin, 1967). In the waters of the Maumee River in Ohio, the count of coliform bacteria (an indicator of raw sewage pollution) may be as high as 24,000 times the maximum allowed by federal drinking standards. Carbolic acid is dumped up to 137 times the allowable maximum, and 17 kilograms of cyanide are put into the river per day (Nelson, 1967). Millions of kilograms of phosphates are allowed to enter Lake Erie. This substance, along with other factors such as nitrogen, is a nutrient source for algal growth. Roughly one kilogram of phosphate will support 700 kilograms of algae (Nelson, 1967). Consequently, Lake Erie is producing vast algal blooms that in turn become polluting factors as the plants die. The water of southern Lake Michigan is so polluted that it is estimated that return to normal would take 100 years, and some authorities feel that the damage is irreversible (Nelson, 1967).

Unfortunately, there is inadequate information on how much water pollution ecosystems can withstand before their natural recycling mechanisms are overwhelmed. In addition, the time rate involved in massive, essentially irreversible changes is not well understood. This means that much coordinated basic research must be done to allow man to control dangerous, drastic changes in ecosystems. Lack of knowledge concerning quantity and rate of change is further complicated by incomplete information about the sensitivity and mortality rate of many species affected by pollutants. These parameters must be known in order to predict how future biological modifications would correlate with shifts in pollution levels. The total picture should be kept in view and not be influenced by economically important species only.

It is vitally important that man begin immediately to control his polluting activities. He must devise, as early as possible, new ways to detect the presence of water pollution and its effects, and he must improve the older methods. Only by knowing the extent of pollution and its sources can he develop proper techniques for its elimination. This means that both applied and basic research must be done now to provide means of maintaining a constant surveillance of possible sources of pollution on a world-wide scope.

Rapid and synoptic detection of pollutants is required in order to accomplish the above aims. We consider two classes of techniques for detecting substances in water: *in-situ* techniques and remote-sensing techniques. Up until the last few years *in-situ* measurements were the basis for all pollution observations, but with the development of sophisticated space equipment new remote-sensing approaches have become available. In many instances the two complement each other.

New types and sources of pollution demand continual development of detection methods.

The great need in measurement of pollutants is probably not in the analytical chemistry field, since well established standard methods are available. Refinement studies continue and new techniques are constantly added and tested. The development of remote-sensing methods, however, should be greatly expanded, with thorough consideration of the possibility of applying present background in standard analytical methods. Monitoring of *in-situ* sensors designed to be emplaced permanently or on temporary basis could be accomplished either by airborne vehicles or by satellites. The sensors would be strategically located, and might range in size and complexity from the single, portable sensing instrument to a battery of automated multitest apparatus, housed in a small laboratory building at the edges of bodies of water or on already established Texas platforms.

Water pollutants can be classified into approximately eight types from the standpoint of remote sensing. The sensing methods are based essentially on analysis of electromagnetic radiation. These eight, listed in the next paragraph, will be presented in more detail in a subsequent section of this report, and other types of pollutants will be discussed briefly under non-remote analytical techniques.

Basically, the pollutants that can be detected by remote sensing are the following: oil pollutants, suspended sediments, chemical and toxic wastes (that are detectable or that produce a detectable effect), solid wastes, thermal effluents, radioactive wastes, nutrient wastes, and living organisms as biological indicators of pollution. On the other hand, pollutants that do not lend themselves to remote sensing, such as heavy metals, must be detected by *in-situ* methods.

CURRENT (NON-REMOTE) TECHNIQUES

Water analysis by analytical chemical techniques has been accomplished for many years. Standard works are available for determinations in both fresh (American Public Health Association, 1965) and marine waters (Strickland and Parsons, 1968). A standard work concerned specifically with the detection of pesticides has also been published (Barry, Hundley, and Johnson, 1963). Procedures are described which, if performed by competent workers, will give consistent, reproducible results. However, accuracy in measurement must be accompanied by relevance in the biological system. All standard works are concerned with non-remote techniques, but they should be examined carefully to determine how they might be used in a data telemetry system.

More recently, many new or expanded analytical methods of a non-remote type that are not included in the standard works have appeared in the literature. They are far too numerous to discuss here. A list of substances, selected as possible pollutants, is given in Table I, together with references (identified by number on page 127) to specific testing techniques that might possibly be adapted to a remote data collection system. Most of these methods would allow the sensors to be placed at properly selected sites for detection and monitoring.

Annually, a review of the literature of water pollution control containing a section on analytical methods is published by the Research Committee of the Water Pollution Control Federation. The literature covers most of the elements and compounds found in both fresh and marine waters. It also includes good discussions of modern techniques and equipment. These pertain to both inorganic substances and the important organic compounds along with their environmental interactions. Each year the American Chemical Society publishes their Annual Reviews which contains a section on water analysis. This is a most comprehensive work covering the world's literature on the subject. The U.S. Geological Survey has also published a manual containing methods to collect and preserve water samples, and to analyze them for 55 properties (Brown, Skougstad, and Fishman, 1970).

New instrumentation also has appeared in the last few years as nonremote techniques have developed. Not all are necessarily more accurate than older methods; but they provide more rapid detection, which is a critical factor in pollution studies, allowing for compilation of more data than might lend themselves to computer use.

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Table I. Analytical Technique/Application Correspondence for Recent Laboratory Procedures

	Spectroscopy	Chromatography	Spectrophotometry	Potentiometry	Flame Photometry	Auto-analyser	Conductometric Titration	Radioactivity	Colorimetry	X-ray	Ion-exchange	Square-wave Polarography	Atomic Absorption	Photon Activation	Ion Selective Electrode	Cation Exchange Resin	Titration	Spectrochemical	Fluorometry	Ultraviolet Absorption	Miscellaneous
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Copper						22												21			
2. Lead												20						21			
3. Zinc			18										19					21			
4. Nickel						22												21			
5. Chromium									17									21			
6. Cobalt									60												
7. Alkali metals				1	6 1	2		4			3						5	7			
8. Hardness metals							8 9 10											21			
9. Aluminum									11				13					21	12		
10. Iron			14			22				15								21			
11. Manganese						16												21			
12. Arsenic												24									
13. Antimony			25																		
14. Mercury			23																		
15. Chloride				27		26								31							

16. Bromide								28		29				31							
17. Iodide						30								31							
18. Fluoride														31	32						
19. Sulfate																33					
20. Phosphates								35											34		
21. Silica											36										
22. Nitrites						37															
23. Nitrates						37									38						
24. pH									40												41
25. Alkalinity									40												41
26. Oxygen		47																		43	42 44 45 46
27. Detergents						50							48 49								
28. Pesticides		51 52																			
29. Herbicides		51																			
30. Organic acids		53	54						40												
31. Phenol	53	55																			
32. Petroleum	58	57																			
33. Carbon		56		56			56										56				
34. Radioactivity								59								59					
35. Cyanide						39															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

(Numbers refer to Author Index on page 127.)

Accuracy and sensitivity are presumably necessary, but they must be considered relative to what is significant in the biological and ecological cycles. Otherwise a usable set of criteria cannot be formulated. This is as important an aspect of pollution control as is the detection of the pollutants.

The use of more sophisticated instrumentation has its problems, however. McFarren, Parker, and Lishka (1968) evaluated an atomic absorption method for detection of metals as applied by a number of laboratories. Cadmium detection was unsatisfactory, and lead could be detected only after a preliminary chelation process. Of ninety-two laboratories analyzing for calcium, magnesium, sodium, potassium, chloride, sulfate, and fluoride, thirty-eight laboratories had perfect results, fifty-two had some unacceptable results, and two had no acceptable results (Greenberg, Moskowitz, Tamplin, and Thomas, 1969).

GENERAL ASPECTS

CAPABILITIES

Synoptic Coverage

Water pollution can often be detected from spacecraft or from aircraft. Potential advantages of remote sensing from spacecraft include global synoptic coverage of the oceans and fields of view sufficient to disclose large-scale effects. The ability of satellites to visit each site of interest periodically and frequently throughout the life-time of the spacecraft (years) serves not only to produce time histories of the changes but also to overcome obscuration by clouds and to secure the economic advantage of low cost per visit.

All-Weather Capability

Essentially all-weather remote sensing is provided by microwave radiation, which can penetrate clouds to map the water surface temperature and roughness. Dynamic topography of the ocean surface (sea-level anomaly) is measurable with microwaves from satellites, thereby enabling ocean current systems to be traced if improved accuracy can be achieved. The thickness, extent, and movement can be observed. Whether these capabilities relate to pollution problems depends upon circumstances. Like infrared, microwaves do not penetrate ocean water significantly, so that sub-surface pollutants cannot be sensed directly.

What Pollutants Can Be Sensed Remotely?

Not every form of water pollution can be sensed and measured remotely. For example, many dissolved chemicals have no discernible remote signature. On the other hand, particulate matter of any kind always discolors otherwise clear water. Some pollutant scatterers have distinctive spectral signatures and others that are themselves neutral enable otherwise invisible colored dissolved substances to be detected. Thus, any pollutant that adds to the scattering and absorption by natural water has a potential for being remotely sensed and measured. Due to the light-attenuation characteristics of water, however, subsurface pollutants can only be detected in the visible and near-visible region of the spectrum.

Thermal pollution of the water surface is detectable from spacecraft and aircraft by several different means. Downward-looking image-forming infrared sensors record the ocean surface in terms of the radiant power it emits. The recorded pattern denotes point-to-point differences in temperature and/or emissivity. Emissivity of the sea surface is affected by its roughness or by pollutants, such as oil.

Oils on the water surface can be seen in photographs either because they alter the surface tension and thereby alter the wave structure and hence the reflection of the sun or the sky by the sea-surface, or because the oils have unique ultraviolet or infrared spectral signatures.

Electro-optical cameras designed to record the ocean surface in a very narrow spectral region entirely contained within a Fraunhofer line respond only to fluorescent radiation. Ocean chlorophyll is a fluorescent substance which can be sensed remotely in this way. Lasers in spacecraft or aircraft may provide active means for remote excitation of marine fluorescence.

Indicators of Pollution

Interestingly, some of the same remotely sensed spectral signatures that disclose the presence of desirable marine resources (e.g., commercial fisheries) may, under different circumstances, reveal the presence of pollution. Chlorophyll is such an indicator. Its presence in the deep ocean may signify standing crops of phytoplankton which initiate the food-chain in the sea and support, thereby, edible fish in commercial abundance. The same phytoplankton bloom occurring in near-shore water, in estuaries, rivers, or lakes may, however, indicate pollution by sewage or other waste materials. A priori information and/or other remotely sensed data can be used to interpret the observed presence of such possible potential indicators of pollution.

Observation of Circulation

In almost all studies concerning aquatic pollution an important element will be the circulation pattern, whether the scale be large or small. It seems self-evident that the effects of oil spills, sewage, biocides, thermal effluents, sediment, and all other potential pollutants will be to a great extent determined by the local circulation. Yet circulation is perhaps the most difficult parameter to measure in the environment. Great progress has been made in the general field of mathematical modelling of circulation in bodies of water, but generally adequate prediction capabilities are not yet available.

It is precisely here that remote sensing has one of its most valuable uses. Inherent in remote sensing is the ability to scan large areas quickly and repeatedly, which is needed to study circulation and which at present is totally lacking in our traditional approach.

ORIGINS OF OCEAN COLORS PRODUCED BY WATER POLLUTANTS

The visible color of the ocean, apart from sky reflection or bottom influence, depends only upon the spectral scattering/absorption ratio. This is ocean color as seen by observers in a hooded glass-bottomed boat (Duntley, 1963).

Many water pollutants produce visible spectral signature (ocean color) by scattering or absorbing daylight. Unfortunately, these signatures are imbedded in the optical signal generated by normal water. Several mechanisms degrade the total sub-surface signal during its transmission to any remote sensor. For example, light from the sun and sky are reflected toward the sensor by the water surface, and furthermore these reflections are complicated by waves and white caps. Sunlight and skylight are also scattered into the sensor's path of sight by particles in the atmosphere, particularly by the water droplets that comprise haze, fog, and clouds. None of this reflected and scattered light contains information about sub-surface water pollutants; it serves only to reduce the apparent contrast of the pollutant's optical signature. If that contrast is reduced below the threshold of the sensor, the pollutant will not be detected.

Modifications to visible-region reflection spectra of water by particulate matter are due to (1) scattering by the particles, (2) direct reflection from large masses of particles, and (3) absorption by materials in the particles. Most particles suspended in water tend to increase reflectance substantially in the middle wavelengths compared to clear water. At longer wavelengths the increase is reduced by the high absorption of water. At short wavelengths reflectance is also decreased, because the high scattering due to water molecules is partially blocked by the particles. Combinations of these effects can result in unique signatures associated with various types and concentrations of particles. Stratification of the particulate matter can also result in a modification to the signatures, usually exemplified by an increase in short-wavelength reflectance and a decrease in long-wavelength reflectance.

Absorptions due to pigments such as chlorophyll a and pycobilin result in a decrease of reflectance in specific spectral regions. The degree of such absorption is typically indicative of the concentration of the particular pigment in the sample.

Petroleum has already been mentioned as a pollutant of the water surface, but naturally occurring vegetable and animal oils are also commonly found on the surfaces of natural waters. Such surface materials can be remotely sensed by all forms of electromagnetic radiation including microwaves, infrared, red light, and ultraviolet, whereas only blue and green light enable sub-surface pollutants to be detected. Some surface pollutants, such as oil, are detected because they alter surface tension at the sea surface, thereby changing the steepness of the tiny capillary wavelets which cover the sea surface whenever air moves across it. Such surface effects are best seen in the edge of the glitter pattern caused by reflection of the sun. They seldom, if ever, have distinctive colors.

ATMOSPHERIC EFFECTS ON REMOTE SENSING

Scattering within the atmosphere limits the performance of remote sensors by degrading the contrast of the optical signatures, even when the path of sight from the ocean surface to a satellite or a high-flying aircraft is free from clouds. Because atmospheric scattering varies with optical wavelength, its effect on contrast must be considered spectrally. In the visible spectrum the atmosphere is effectively free from absorption unless smoke, smog, or dust is present. A few very narrow, weak absorption lines due to atmospheric gases do exist, but they cause no significant effect with respect to remote sensors employing normal spectral band-widths. In this respect the visible spectrum differs markedly from the infrared, where absorption phenomena are strong, complex, and usually dominant in determining the design and performance of remote sensors.

Water containing a pollutant that can be remotely sensed by visible light differs in its spectral reflectance (i.e. spectral signature) from pollutant-free water. Often the polluted area forms a streak or patch in the ocean, lake, or river. Thus, it is useful to specify the optical signature in terms of spectral contrast, i.e. the fractional difference between the reflectance of the polluted area and that of the surrounding non-polluted water, as follows:

$$C = \frac{R_p - R}{R}$$

where R is the directional spectral reflectance of non-polluted water, R_p is the corresponding reflectance of the polluted area, and C is the *inherent* spectral contrast of the polluted water in the direction of the remote sensor. All three of these quantities vary not only with optical wavelength but with the way in which the water is illuminated and with the direction in which it is viewed by the remote sensor. Wind velocity at the water surface also has an important effect.

At the remote sensor the *apparent* spectral contrast C' is always less than C, as a result of scattering throughout the atmospheric path of sight. The ratio of C' to C is called the *contrast transmittance;* its value does not depend upon the reflectance R_p of the polluted water but is a combined characteristic of the atmospheric path and the nonpolluted water (Duntley, Boileau, and Preisendorfer, 1957) (Duntley et al., 1964).

The spectral contrast transmittance of atmospheres is highly variable. It depends not only upon the atmospheric constituents but also upon the directional character of the lighting and upon the direction and length of the path of sight. Extensive bodies of data measured from aircraft, spacecraft, and ground stations exist, but there is no readily available compendium. Some typical examples are given in Table II; the data are extracted from unpublished files of the Visibility Laboratory of the Scripps Institution of Oceanography in La Jolla, California. They summarize measurements of vertical contrast transmittance at sea on approximately 200 "clear" days when the sky appeared blue and cloud-free overhead to shipboard observers. In each instance the solar zenith angle was about 45° and the measured data refer to the entire vertical path of sight to the ocean surface from orbital altitude. "Red", "green", and "blue" refer to broad spectral bands centered roughly at 650, 550, and 450 nanometers, respectively.

TABLE II

VERTICAL CONTRAST TRANSMITTANCE OVER THE OCEAN FOR DOWNWARD PATHS OF SIGHT FROM EARTH ORBIT ON "CLEAR" DAYS

(Surface wind: 0 to 7.7 m/sec; Solar altitude: 40° to 50°)

	Best day measured	Average of 200 days	Worst day measured
Red	0.90	0.70	0.50
Green	0.50	0.35	0.20
Blue	0.35	0.20	0.05

SOME SPECIAL REQUIREMENTS FOR REMOTE SENSING OVER WATER

Water is subject to all modes of translation and deformation, both horizontal and vertical, but the spatial distribution of properties generally shows only very gradual changes. Thus the requirements as to mapping accuracy are typically much less over the sea than over the land. The temporal resolution requirements, however, are much greater than are needed over the land. Mixing occurs freely in oceans, lakes, and seas although, due to density stratification, one hundred to ten thousand times more actively in the horizontal than in the vertical plane. Accordingly, much sharper discontinuities are maintained in vertical than in horizontal sections, and sensors that map the oceans in plan view are called upon to discriminate large features with weak contrast between adjacent areas. Since the locations of such features are subject to change from day to day, relative position is of more importance than absolute position on the ocean compared to the land.

The distinctive appearance of a patch of water is frequently due to a cloud of suspended particles whose density differs from that of water and which hence acquire a vertical motion through the water. Light particles rising from lower levels into the moving surface layer would then seem to flow as from a two-dimensional "source"; conversely, heavy particles flowing along the surface would seem to disappear as into two-dimensional "sinks".

The observables on the ocean are frequently deployed in long lines along the direction of the local surface currents. Examples are oil slicks and trash lines floating on the sea surface. Since the lines may be fairly narrow, fairly sharply imaging sensors would be needed to observe them. (Such cases would contrast with those mentioned previously that are characterized by large areas with vaguely defined boundaries).

The transmissivity of water to electromagnetic radiation differs from that of the atmosphere in fundamental ways important to remote sensing over water. The most obvious difference is that, rather than a large number of windows, as in the atmosphere, only one broad window exists in water.

For distilled water and for clearest ocean water this window is centered near 480 nanometers.

For the foregoing reasons, an argument can be advanced against designing a single instrument system for use over both the land and the high seas. However, with the growing interest in pollution and other problems that are intimately related to the near shore and estuarine environment, characteristics intermediate between those for high seas remote sensing and those for terrestrial remote sensing emerge as dominant requirements of an effective system. The ideal system must include capabilities for both oceanic and terrestrial reconnaissance; accordingly it is imperative that every effort be made to design for commonality, provided this can be done without unacceptable compromise of the requirements for each major use.

POLLUTANTS

OIL

Now that huge quantities of crude oil and oil products are transported in ships, the problem of oil pollution, both of surface waters and benthic communities, has worsened considerably. In addition, offshore drilling of oil wells has introduced localized but important pollution problems. These are sure to increase in importance as the Atlantic Coastal area is opened to exploration for oil deposits. Roughly speaking, oil spillage is linearly related to oil transportation by water and indirectly to the energy demands of the burgeoning world population. The consumption of energy from all sources is expected to double by 1980 (SCEP Report, 1970).

Oil discharges into the coastal and estuarine waters are known to be responsible for loss of wildlife and commercially valuable fish and mollusks as well as affecting recreational facilities and the aesthetics of our natural aquatic environment. Six principal sources of oil pollution destructive to ecosystems have been identified (Federal Water Pollution Control Administration, 1968). These are:

1. Sudden and uncontrolled discharge from wells toward the end of drilling operations.
2. Escape from wrecked and submerged oil tankers.
3. Spillage of oil during loading and unloading operations, leaky barges, and accidents during transport.
4. Discharge of oil-contaminated ballast and bilge water into coastal areas and on the high seas.
5. Cleaning and flushing of oil tanks at sea.
6. Spillage from various shore installations, refineries, railroads, city dumps, garages, and industrial plants.

The major question, the answer to which is unknown, is the degree of damage to the environment that may result from various quantities of oil discharge.

It is difficult to assess the total volume of oil discharged into the world's waters. The SCEP Report made estimates of the direct discharge, shown in Table III. The amount of oil from natural leaks may be as great as the amount released by man; however, there is no reasonable way to estimate this form of oil pollution, as the leaks occur at low rates of flow and are dispersed over large areas.

TABLE III—ESTIMATES OF DIRECT LOSSES INTO THE WORLD'S WATERS, 1969

(AFTER SCEP, 1970)*

Source	Loss Metric Tons/Year	Percentage Of Total
Tankers	530,000	25.4
Other ships (bilges, etc.)	500,000	24.0
Offshore production	100,000	4.8
Accidental spills		
Ships	100,000	4.8
Nonships	100,000	4.8
Refineries	300,000	14.4
In rivers carrying automobile wastes	450,000	21.6
	2,080,000	100.

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The damage caused by a spill may range from slight to very significant. For example, North, Neuschul, and Clendenning (1965) showed that it required two years for extensive recovery to occur after the 9,000 cubic meter spill of oil from the tanker Tampico in March, 1957. After four years, seven species of animals present before the spill had not been found. Similar examples are given in the work of Blumer (1969) (Referenced in SCEP, 1970).

In case of a spill or similar event, the nature and extent of the oil pollutant must be promptly established so that corrective actions can be taken. Planning and initiation of efficient clean-up or containment requires knowledge of the material, volume, and areal extent, the source of oil, and the nature of the circulation (currents, tides, wind, waves, topography, and water density). Detection and evaluation of an oil discharge must be prompt because water-soluble substances are extracted from the oil and solid aggregates settle to the bottom, making a true assessment of the discharge more difficult and also increasing the likelihood of damage.

The detection, evaluation, and monitoring of the surface features of an oil spill are amenable to remote sensing techniques. The same approach can also monitor the environment for changes after the spill for extended periods of time. Oil and petroleum products have several properties appropriate to this form of detection. Oil has a specific gravity less than water so that it initially floats. The surface tension characteristics of oil are considerably different from those of water, and this difference significantly alters the capillary wave structure (Ewing, 1950) (Garrett and Bultman, 1963). The ratio of brightness temperature to true temperature of the surface depends on the effective emissivity of the water. This varies from 0.3 to near unity for reasons not clearly understood but probably related to the spectrum of ripples and to the foam present on the sea surface. It therefore appears that microwave radiometry through clouds is basically capable of detecting the smoothing of capillary ripples by oil films. Oil is highly reflecting in the ultraviolet portion of the spectrum, whereas water has relatively low reflectance (Chandler, 1970). Oil also has fluorescence properties in the visible region that could be used as basis for a monitoring method (Fantasic, Hard, and Ingroo, 1971).

These characteristics of oil, when regarded from the standpoint of remote sensing, suggest the following rationale for development of an oil surveillance system. Initial surveys for detection, identification, and monitoring must be accomplished promptly and without regard to weather or to the amount of available light. For this reason the initial detection systems should rely primarily on the use of microwave sensors, either active or passive. Radar systems already have been used to monitor oil spills (Guinard, 1971), and if used with repeated coverage can determine dispersal rates and directions of oil movement. Multi-frequency microwave radiometers can theoretically determine oil thickness from about 0.05 millimeters to greater than 1.2 millimeters (Hollinger and Mennella, 1971).

As the oil disperses to thin layers, the use of remote sensors in the microwave region may continue to delineate boundaries, but thickness may have to be determined by fluorescence rather than by microwave observations. Observations in the ultraviolet and visible region may also be used, but film thickness measurement may not necessarily be accomplished thereby. Imaging in the thermal infrared region has been used by many investigators with quite varying results as the oil spill may be warmer, colder, or at the same temperature as the water, which at best leads to an uncertain delineation of the oil feature (Stewart, Spellicy and Polcyn, 1970).

As observed in the SCEP Report, oil spills are localized and most likely to occur in near-shore areas. However, because accidental oil spills may occur anywhere, the problem assumes global proportions. Wide spatial coverage may be required for a large spill or leak, with follow-on environmental monitoring over an extended surrounding area. Spectral resolution does not appear to be critical for any remote sensing technique and conventional broadband sensors in the visible and ultraviolet regions may be used with success, as well as microwave systems. Frequent coverage may be desirable in the period just after the oil spill. Look angles appear to be critical only for visible-region sensors, which show the best contrast between oil and water when observations are made taking advantage of glitter pattern geometry with respect to the sun.

The spatial, spectral, and temporal requirements for remote sensing of pollution are summarized in Table IV in the instrumentation section.

SUSPENDED SEDIMENT

Due to the spread of cities with the concomitant building and soil disturbances, more and more shifting of soil into water basins and drainage systems is occurring. This is causing extensive disturbances of the estuarine and salt marsh habitats and it is increasing the proportions of suspended material, causing greater turbidity, of coastal ocean and lake waters. Dredging, dumping of tailings, and filling-in have caused notable changes in many areas. For example, it is estimated that in the last 14 years there has been a 5.4% loss of the total coastal wetlands habitat and a 4.1% loss of shoal-water habitat in the Atlantic Coastal States (Spinner, 1969). Man and his activities are by no means responsible for all sediment movement, and there is rather wide divergence of opinion as to just how to partition the total load between natural causes and man-made causes. One such study (Grissinger and McDowell, 1970) estimated that man was responsible for about sixty percent of the sediment load. It is evident that man is responsible for at least some of the sediment that reaches the waters, and that sediments are intimately involved both directly and indirectly in water pollution and are therefore part of the problem.

Sediment interacts in several ways to create problems. When suspended it reduces water clarity and sunlight penetration, thereby affecting the biota. It settles to the bottom and can bury and kill vegetation or alter the benthic biota. It fills channels and harbors, requiring expensive remedial measures.

Although we know much about problems caused by sediment, we need to know much more about how sediments, through their surface activity, interact with heavy metals and affect the general water chemistry. The whole subject of chemical-ion pollutants is involved with sediments and absorption. We also need to be able to partition the suspended particulate load into sediment and plankton.

Fortunately, turbid water is clearly visible from space and we already have on hand much of the technology needed to assist us. Remote sensing of discolored water masses is by far the most efficient way to examine the broad problem because (1) the water masses need to be examined over broad areas, and (2) the water masses need to be examined continually over an extended time period. Except on a very small scale, we cannot do this now by traditional sampling methods.

As will be noted briefly in the discussion on remote sensing of detergents, one of the primary research requirements for the study of eutrophication is the surveillance of water transparency. Water transparency is related not only to the concentration of dissolved matter but also to the concentrations of solid wastes, sediments, and biota. Several studies have been made using black and white, color, and false-color photography, to define visible-light responses of water with relation to pollutants. Mapping ocean water clarity by spacecraft photography was shown to be feasible by studies of 70-mm color transparencies from Gemini flights (Lebley, 1968). A prototype global map of coastal ocean water turbidity was constructed on the basis of the relationship between water transparency and its color and the visibility of shoals. For comparison, in-situ transparency data taken by oceanographic ships were mapped. The resulting global maps of coastal water clarity indicate that about 35 percent of the world's coastal sea floor can be mapped out to 20 meters depth by aerial photogrammetry. In an experiment using aerial color infrared photography taken at altitudes of 600 and 1800 meters the effect of dredging on the physical and chemical characteristics of water in a lake were shown (Stewart, 1969). The turbidity of the water in the dredged lake was about seven times greater than in any other similar lake. To the eye the water had a muddy appearance, which probably was due to a colloidal suspension of clay caused by dredging. Two other similar lakes showed a turbidity difference caused by the fact that one had dikes which restricted the drainage area size and minimized pollution, with a corresponding reduction in turbidity.

It is potentially possible to distinguish the various suspended materials through some new remote sensing techniques, such as the computer-adapted, electro-optical imaging system called a "Digital Photometric Mapper," results with which have been recently reported (Halajian and Hallock, 1971). The effect of water surface roughness on turbidity data was made relatively insignificant by observing at the nominal Brewster angle and through the V-polarized filter. Conversely, near-grazing viewing through the H-polarized filter was optimum for observing surface phenomena, in particular, for mapping the sea state. Aerial and ground truth measurements check with analytical models in showing an inverse correlation between polarimetric trends of metropolitan New York waters and their levels of turbidity.

Because of the selective scattering properties of sediment particles, remote visible region spectrometry offers potential for determining particle size distribution and types. Inasmuch as discolored, sediment laden water is observable and can be traced, it can be extremely useful for gaining understanding of water circulation, and water circulation itself is basic to nearly all pollution problems.

CHEMICAL AND TOXIC WASTES

Ever since man began to manufacture items with unwanted byproducts, he has dumped his industrial wastes into streams, lakes, ponds, and the oceans. At the present time in the United States these wastes represent about twice the volume of public sewage or the equivalent of the untreated sewage of about 200 million people (Nelson, 1967). Often this material (acids, strong bases, and heavy metals) is highly toxic. The tradition has been to simply dump the wastes with no treatment. Because of the expense and problems involved in treating and/or recycling most wastes, great care is frequently taken to hide the disposal of industrial wastes from the public view. Special pipes are often installed to carry wastes away from the plant, much dumping is done at night, outlets are placed in the bottoms of rivers and lakes, and deep-well injection is sometimes used. However, as noted in the SCEP Report, 1970, "In the terms of familiar economic analysis, the injuries done to the environment and to the society by pollution are 'external costs' or 'social costs', not taken into account in the ordinary business calculations of income and expense. They have been 'external costs' not for reasons inherent in the nature of things or derived from the fundamentals of economics but because the legal system has so provided. In the large and in the long run the legal system reflects the prevailing values and priotities of the society, and it changes as social values change. By appropriate changes in the law, costs previously social and external can be internalized as economic costs to an enterprise that generates them. Such an internalization would represent one application of the principle of source (or protosource or secondary source) responsibility"

Biocides also enter into water as a major pollutant. Over 317 million kilograms of biocides are now used per year, and the quantity is expected to increase at least 10 fold in the next 20 years (Nelson, 1967). Biocides are used all over the world in an effort to control insects and unwanted plants. Many of these degrade slowly and consequently may become concentrated as they pass through many biological components of the food chain. Therefore, these chemicals are involved in accelerating mortality rates in many organisms for which they were not intended. DDT, for example, has been detected in organisms and water over the entire globe.

Detergents, fertilizers, and chemical by-products of manufacturing are pouring into our waters either by dumping or run-off or by passage through sewage systems unchanged by the processing. All of these produce problems, either as abnormal increases on nutrient matter or as actual toxic substances that produce heavy mortality in organisms. Some of these pollutants, even though initially at a lower than mortality level, may become concentrated up through the food chain or may gradually accumulate in the individual, producing lowered vitality or interfering with the fertility of many organisms.

The specific pollutant, be it lead, mercury, DDT, or other toxic waste, may not be capable of being sensed directly, due to low concentration or lack of characteristic spectra. However, there are secondary characteristics of many of the effluents associated with the specific pollutants which make it possible to detect an anomalous condition in the water body. First, the spectral properties of the effluent containing the pollutant may be different from those of the receiving water. Second, the effluent may be at a different temperature than the receiving water and thus subject to thermal detection. Third, the presence of toxic materials can, in some cases, be *inferred* through the destruction or anomalously low concentration of biological indicators, such as phytoplankton (Harris, White and MacFarlane, 1970; Menzel, Anderson and Randtke, 1970).

Remote sensing appears to be an excellent tool for monitoring these types of water pollutants. Acid mine drainage, for instance, has been mapped under favorable conditions using a thermal mapper (Ahmad and Ghosh, 1971). This method is based on the exothermic reaction of pyrite when it is exposed to air and water. It is important to point out, however, that this type of monitoring will probably only indicate that a problem exists but will not, in general, make it possible to identify a specific substance in the effluent. Future sensors like the Fraunhofer Line Discriminator, Pulsed Laser System, or Multichannel Scanning Radiometer may make it possible to remotely detect and identify specific pollutants. By and large, however, water sampling must be done to determine specific types and concentrations. An integrated network of sampling stations which could be interrogated by satellite would thus be a useful component of any environmental monitoring program.

SOLID WASTES

Man has not been a tidy animal with respect to his own biological waste products. As long as populations were low, nature's recycling ability was able to accommodate such material. Unfortunately, water provides a cheap, easy, and natural carrier or flushing agent to take noxious material out of sight and smell; and man's practices concentrate these products in waters and thus remove them from the natural recycling process in a terrestrial situation. At the present time, in spite of costly efforts, the effluent discharged today in the United States is equivalent to the untreated sewage of 100 million people (Nelson, 1967).

In many areas sewage systems do not exist, and human wastes enter into septic tanks. These often overflow into the natural drainage pattern and may contaminate ground water sources extensively. An additional problem related to sewage is that most communities have joint storm and municipal sewage systems. Thus, during peak loading periods and during rainstorms the sewage treatment plant must handle an increased amount of water, overloading the system and causing untreated wastes to be dumped into nearby bodies of water. This, too, is further complicated by the tremendous growth rate of our cities, which places an increased demand on the sewage plants. Communities that can afford it are attempting to separate the two sewage systems but few are able to succeed.

In addition to human wastes one must also consider the millions of kilograms of animal wastes that are produced each day in this country and go untreated. Many beef producers, for example, have adopted the cattle feedlot as the best method for fattening large numbers of beef cattle. The system is efficient and economical but the concentration of waste is an environmental problem. The feedlots are invariably located adjacent to a stream so that the cattle do not have to walk a great distance to drink, and while percolation from the feedlot pollutes the ground water, surface runoff pollutes the stream.

The dumping of raw sewage leads to a variety of problems. It causes eutrophication, lowers the water quality, eliminates the recreational potential of the stream or lake, and can cause disease and shellfish contamination.

Present methods of sewage monitoring and measurement consist of water quality sampling and recording the input/output statistics of each treatment plant. These methods are not adequate, however, to present a true picture of the situation. There are not enough *in-situ* monitors, instruments are often placed in the wrong locations to measure water quality, and plant statistics only deal with sewage that is transported to the plant. Also, these types of data do not provide information regarding the environmental effects of sewage.

Remote sensing offers several advantages over conventional means of monitoring and measuring sewage discharges. First, with the synoptic view that spacecraft and aircraft sensing gives, it is possible to inventory and catalog the treatment plants in a region or within a river basin. Using photography, new pollution sources may be found and a study of the movement and fate of all sewage effluents can be made. Some recent measurements using a rapid scanning spectrometer in an aircraft has demonstrated the ability to remotely determine concentrations of solid wastes as well as differentiate between solid wastes and other particulate matter in the water (White, 1970).

The identification of a specific effluent with a sewage plant requires data with resolution of the order of 5-10 meters. Major effluents should be detectable with 100-meter resolution. As indicated in Table IV (see p. 162), however, useful information can be obtained from data with 200 meters resolution.

A second advantage of remote sensing is that one can view the scene in different parts of the spectrum. By using sensors operating in the thermal portion of the spectrum it is possible to observe effluents day or night and to detect effluents which may not appear on the visible imagery. Thermal infrared imaging is extremely useful in studying the subtle surface temperature patterns and mixing characteristics of the effluents and in determining where to locate sampling devices and *in-situ* monitors.

A third advantage of remote sensing is that by collecting temporal or time variance data it is sometimes possible to locate leaking septic tanks or contaminated ground water systems by detecting their secondary effects on the surrounding environment. These are usually noticeable in the spring when water containing sewage can cause an early growth of vegetation in a backyard or along a stream fed by a contaminated spring.

Finally, by putting all of this information together and by studying the urban development trends of the region one can begin to suggest what the effects of sewage on the environment are and will be. Even today huge algal blooms can be seen from the air near sewage plant effluents, and beaches, parks, housing areas, etc. affected by them can be quickly detected.

THERMAL EFFLUENTS

Water has been used extensively as a coolant in many manufacturing processes. Heated water is discharged into the original source, often causing a rise in temperature from 2℃ to 10℃ (Environment Staff Report, 1970). Temperature elevations of this magnitude exceed temperature tolerances of many species of animals and plants. Chemical reactions will be accelerated and solubility of important gases (such as oxygen) in water will be considerably reduced. With the projected increase in the number of nuclear power plants, greater quantities of heated water will pour back into drainage systems, lakes, and even the oceans. The predicted California coastal power plant capacity for 1980 will require one thousandth of the estimated California current (elevated 1°C) for cooling (Useful Applications of Earth-Oriented Satellites, 1969).

Surface temperature is one of the principal ocean features that have been most frequently measured by remote sensors. Remote infrared sensing of water surface temperature from an airborne platform is now being accomplished on a routine basis by many organizations (Weiss, 1969). Over the past few years commercial radiometers with accuracies (from low altitudes) of a few tenths of a degree Celsius and sensitivities of a few hundredths of a degree Celsius and covering a temperature range from 173 Kelvin to a few hundred Kelvin have become available. Since there is a need for frequent and accurate measurements of the sea temperature on a global scale, a satellite equipped with infrared sensors becomes a worldwide detector which may be used to provide these data.

The mapping of the thermal properties of the ocean surface has been accomplished by infrared radiometers on the Nimbus and ITOS (Improved TIROS Observation Satellite) series of satellites (Sherman, 1969; Leese, Pichel, Goddard and Brower, 1971; Rao and Strong, 1971; Rao, Strong and Koffler, 1971). The ITOS infrared data have been processed to give an RMS difference between infrared measurements and ship observations of 1.6°C to 1.8°C. Part of the discrepancy between ship and satellite observations is due to errors in the former—a study of ship observations has shown a standard error of 0.9°C with positive bias (Saur, 1963).

As with any remote sensor, surface observations taken from point sources over limited areas are inadequate for comparison with measurements by satellite instruments with wide coverage. The "ground truth" should be representative of an area equal to that whose temperature is read by the

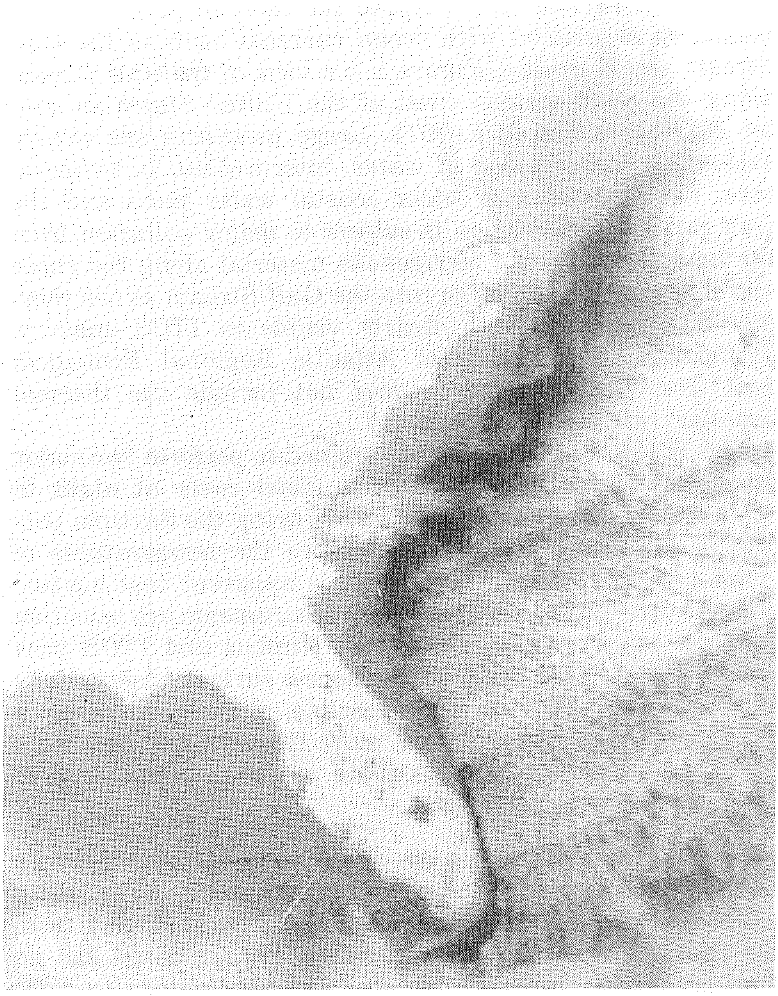

Figure 1.—View of the Gulf Stream along the southeastern coast of the United States as seen by ITOS-I on March 5, 1971.

satellite sensor. This implies observation either from large fields of buoys or from low flying aircraft.

Specifically, the High Resolution Infrared Radiometer (HRIR) and the Direct Readout Infrared Radiometer (DRIR) on ITOS-I have mapped the thermal gradients and meanders associated with ocean currents such as the Gulf Stream and Kuroshio. Figure 1 is a view of the Gulf Stream along the Southeastern coast of the United States as seen by ITOS-I on March 5, 1971. Large meanders are clearly evident. A large region of water, intermediate in temperature, lies between the colder coastal water mass and the Gulf Stream. This region is subject to major pollution from the land. The input of terrigenous material along the shore and its eventual discharge into the Gulf Stream at the thermal boundary are both clearly visible in ITOS imagery. (Unfortunately the Central Atlantic Regional Ecological Test Site (CARETS) area does not include the thermal boundary with the Gulf Stream.)

The HRIR and DRIR were designed to perform two major functions: (1) to map the earth's cloud cover at night to complement the television coverage during the daytime portion of the orbit; and (2) to measure the temperatures of cloud tops and terrain feature. It is apparent that surface temperature data generated by the instruments are sensitive to cloud conditions. Satellites like Nimbus and ITOS pass repeatedly over the same areas; hence, surface observations of any region will always be possible, since cloud cover is only temporary. However, the more frequent and extensive the cloud cover, the less adequate are the observations of dynamic thermal phenomena.

One of the problems with space observations of water bodies is knowing the location of the subsatellite point. With land observations, the area can usually be identified from the characteristic terrain features; but if an image has no familiar land features, only water, the location can be difficult to identify and its information value is thereby reduced. This has been found true both in space photography analysis and in space infrared imagery.

A factor of considerable importance in understanding the effects of thermal effluents is the nature of the circulation patterns in the discharge region. Meteorological and tidal effects on the patterns must be understood before logical design and control requirements can be imposed on the installation that produces the effluent. Water surface temperature can be used to establish circulation patterns, at least at the surface, and these patterns can be used to validate hydraulic models for a given river, estuary, or coastal region.

In September, 1970, the New York State Atomic and Space Development Authority completed a two-year "heat picture" of the state's major bodies of water (Yulish, 1970). It was said to be the first time that infrared scanning had been used on so vast a scale. The information will serve as a guide in selecting locations for power plants and in monitoring their discharges in order to protect the ecology. Carried in a low-flying airplane, the infrared thermal mapper, sensitive to temperature changes as small as 0.6°C, provides a thermal image of the water surface in which darkness increases with surface temperature. The results, printed on 70 mm film, resemble a topographic contour map. The imagery not only reflects natural variations in surface water temperature caused by seasonal influences, geography, flow, depth, tidal effects, etc., but also demonstrates how heated water from artificial sources such as power generating stations, sewage treatment plants, or factories are all subject to the same complex influences.

An initial experiment to investigate the time scale of dominant thermal features on the surface of Lake Ontario was carried out in May and June of 1970 (Elder and Thomson, 1971). Infrared imagery in the 8-12 μm atmospheric window was obtained for a specific location on Lake Ontario. The imagery was done with a Reconofax IV scanner mounted in a light aircraft. A number of flights were made in order to provide a temporal comparison of the dominant thermal features on the lake surface. Most of the imagery was taken at an altitude of 900 meters. Surface observations in the form of lake surface temperatures and meteorological measurements were available from ships in the area. Ground data were also provided by a Barnes PRT-5 radiometer which was flown in the aircraft at the same time as the scanner. The individual scanner traces have been arranged in a mosaic, which facilitates the identification of large scale features.

Microwave radiometric techniques have been theoretically developed to provide continuous, all-weather monitoring of sea conditions from satellites. Data acquired with microwave radiometers from earth orbiting satellites could provide previously unattainable up-to-date information on sea state and sea temperature over the entire earth. To date, determinations of sea state and sea surface temperatures have been acquired as a result of local measurements and observations made either with *in-situ* devices or visually from low-flying aircraft. Obviously, only limited coverage is possible through the use of these techniques, and significant data cannot be made available on a timely basis. What is needed is an operational remote sensing system by which measurements of sea state and sea temperature can be made from a spacecraft on a worldwide basis and reported in a timely fashion (Ewing, 1969). It is believed that such a capability is possible through the use of passive microwave radiometry.

RADIOACTIVE WASTES

The danger from naturally occurring radioactive isotopes entering the earth's waters is essentially insignificant. Because of man's success in creating isotopes at will, however, the danger from artificially created isotopes may become important. Radioactive effluents from nuclear power plants and fallout from atomic tests have become the main sources of marine water radioactive contamination. Measurements in the Columbia River 550 kilometers downstream from a nuclear reactor showed a flow of 1 curie (4×10^7 disintegrations/sec) per day (Davis and Foster, 1958). U. S. Geological Survey radiation studies have disclosed anomalous aeroradioactivity over the Columbia River within the Hanford AEC reservation and for many kilometers downstream. This aeroradiation could not be due to natural effects, because only a few centimeters of water will completely absorb the natural radioactivity of soil and rock. Therefore, the aeroradiation appeared to originate from radioisotopes in the water resulting from activities of the Hanford plant.

Many of the isotopes have short half-lives, but some, such as chromium-51 and zinc-65, have been found in pelagic organisms out in the Pacific Ocean some distance from the mouth of the river. Potassium-40 is perhaps the most common contaminant, representing over 90% of marine radioactivity. The total amount of such contaminants may be slight but a built-in danger exists: As radioisotopes go through different trophic levels of the food chain the tendency is for the isotopes with longer half-lives to be concentrated until they may have a significant effect. Some isotopes are known to be concentrated by a factor of four in a tertiary consumer, such as fishes, in a food web (Scott-Russell, 1966).

Nuclear energy is often called the power source of the future. One of its stated advantages over conventional means of generating power is its cleanliness: it has no dirty coal piles, smoke, and SO_2 fumes, and the plants may be attractively designed and landscaped. However, there are two negative aspects of nuclear power generation: (1) the enormous quantities of water needed for cooling purposes, and, as mentioned above, (2) the release of radioactive particles into the environment. The heated coolant water can cause thermal pollution and disrupt the ecological balance of a water body; but the effects of radioactive effluent and waste remain a subject of dispute. Remote sensing has a role to play in the detection of radioactive emission (North and Kiefer, 1971). Although limited to low altitude detectors (200 meters above terrain), airborne scintillation detectors can measure the levels of radioactive emission from a surface area, and the standards established by the AEC can be used to determine whether the levels are within recommended tolerance limits. Data of this type are useful in detecting variations in radioactivity such as might result from nuclear testing, nuclear reactors, or radiation accidents.

The scintillation equipment accepts only pulses originating from gamma radiation with energies greater than 50 Kev. The gamma-ray flux at 200 meters above the ground has three principal sources: cosmic radiation, radionuclides in the air, and radionuclides in the superficial layer of the ground. Radioactivity data can be corrected for deviations from the 200 meter sensing elevation, and for the cosmic ray component. The component due to radionuclides in the air at 200 meters above ground is difficult to evaluate. However, if atmospheric inversion conditions are avoided, the air component may be considered to be fairly uniform on a given day in a particular area and will not affect the discrimination of the radioactivity levels that reflect changes in the ground component. The ground component consists of gamma rays from natural radionuclides, principally members of the uranium and thorium radioactive decay series, and potassium-40. Fallout from radioactive nuclear fission is also part of the ground component.

Remote sensing of a radioactivity contaminated surface area of the ocean at the site of an underwater nuclear detonation has been performed. The results of the study indicated that an aerial survey is an effective method of obtaining radiation intensity as well as the outline and location of a contaminated area at any time after an underwater nuclear detonation. An aerial survey is more efficient than a surface ship survey in locating and defining the outline of a contaminated area, and also entails less radiation hazard to survey personnel.

NUTRIENT WASTES

The most basic environmental process occurring on earth is photosynthesis, the first link in the marine and land food chain and the only significant process by which solar energy is converted to a form that supports life. The rate of photosynthesis is governed, in most instances, by the availability of inorganic nutrients, such as nitrogen and phosphorus (Ryther and Dunstan, 1971). These nutrients are provided to water bodies through either man-created or natural means. It is believed that phosphorus and nitrogen are the fertilizing elements most responsible for excessive growth of algae and weeds, although vitamins and trace metals also affect the growth of algae (Mackenthun, 1969).

To properly assess a nutrient problem, consideration should be given to all of those sources that may contribute nutrients to the water body. In open oceans the availability of these nutrients is limited and the rates of photosynthesis are quite low. In the coastal marine environment, in estuaries, and in lakes the levels of nutrients are much higher, due partly to natural sources, such as upwelling, wave and tidal action, river overflows, etc. and partly to man-made sources, such as human waste, detergents, agricultural fertilizer runoff, and industrial wastes.

Eutrophication is the change in a body of water, usually a pond or lake, (although the term may also be applied to semi-enclosed bodies of salt water), during which the plant life and animal life therein increase in abundance and complexity due to an increase in the amount of nutrients supplied to the water body. The process may be beneficial if held within limits, but catastrophic if excessive. One of the first effects of eutrophication is an exaggerated diurnal cycling of the oxygen content of the water body. During the day, the action of photosynthesis can supply enough oxygen into the water to cause saturation; during the night, when no oxygen is supplied by photosynthesis, the metabolic demand for oxygen by the entire biomass can deplete the oxygen with the attendant destruction of many of the desirable life forms; the decomposition of the dead organic matter often depletes the oxygen supply seriously. A second effect of eutrophication is a decrease in the depth of sunlight penetration. Phytoplankton and other organisms that are below the depth of the euphotic zone place a heavy demand on oxygen, with the result that oxygen depletion in bottom waters becomes continual and progressive.

It usually is not possible to remotely sense specific nutrient wastes in a body of water. Only if these wastes are contained in an effluent that directly affects the absorption and backscatter of sunlight can they be sensed by means of conventional camera or multispectral-imagery systems. The presence of these nutrients can, however, be inferred through the presence of phytoplankton, a direct result of the presence of nutrients. Indirect detection of oxygen lack may be carried out through the use of photography or spectrometry which will reveal the presence of dead organisms, the reduction in the abundance of live organisms (usually plants), a change in species composition, or the occurrence of indicator species. All photosynthetic processes occurring in water require chlorophyll. Highly significant correlations have been found by Lorenzen (1970) between chlorophyll concentration in surface waters and primary productivity, euphotic zone chlorophyll, and euphotic zone depth. The presence of chlorophyll is thus a key indicator of basic biological processes and can be used to evaluate eutrophication of a body of water. Since an inflow of nutrients causes an increase in phytoplankton and thus an increase in chlorophyll, the concentration and distribution of chlorophyll in a body of water can also be used as an indicator of the concentration and distribution of nutrients in that body of water. The ability to quickly and repeatedly monitor photosynthetic activity from a remote platform would be a strong step towards delineating and understanding the eutrophication of water bodies due to nutrient inflow.

Instrumentation that can be utilized to delineate areas of strong phytoplankton bloom resulting from nutrient inflow include the multiband camera system and the multispectral scanner. Instruments potentially capable of quantitative measurement of surface concentration and distribution are the chlorophyll correlation radiometer and the multichannel scanning radiometer/spectrometer.

LIVING ORGANISMS

Introduction of Species; Disturbance of Ecological Relationships

Generally, man is involved in the initiation of biological pollution. Such pollution is often responsible for the rapid and frequently disastrous change in the interspecies relationships in an ecosystem. For example, the inadvertent introduction of the marine lamprey *(Petromyzon marinus)* into the Great Lakes System by the construction of the Welland Canal represents biological pollution. The introduction of this parasitic species into an ecosystem in which a normal host-parasite relation of this sort did not exist apparently brought havoc to native lake species, particularly such predator species as the lake trout. The proposed construction of a sea-level canal through Central America would allow Atlantic and Pacific waters to mix and would undoubtedly cause another instance of disturbing ecological relationships that have evolved over millions of years. Building of dams for flood control and to provide hydraulic power invariably brings about disruption of associations of species that have undergone long evolutionary developments of relationships. Many of the major free-running streams in the United States now have one or more dams.

The water run-off systems of the world are now in danger of biological pollution. The water hyacinth *(Eichornia craisipes)* now pollutes every major tropical and subtropical fresh water system of the world. A small aquatic fern *(Salvinnia auriculata)* has been introduced into many dammed areas. It produces a complete carpet of plants on the surface, causing major interference with light penetration and temperature relationships and disrupting exchange of gases.

Heedless tampering with species within an aquatic system also causes biological pollution. In the southwestern Pacific Ocean 30% to 40% of the coral reefs have been destroyed by sudden and enormous predation by a starfish *(Acanthaster planci)*. This species destroys reef-building coral animals, thereby producing essentially dead reefs. Fish desert such areas, and the reefs are also subject to erosion. This latter aspect will undoubtedly change many island habitats, as well as lagoon associations, or may cause them to disappear entirely. Ocean currents may be influenced, and thus local weather patterns may be disturbed. The rapid population increase of the starfish is thought to be the result of man's removal of the giant triton snail, which is a natural predator of the adult starfish, and the indiscriminate blasting of coral growth in harbor construction. Apparently, adult coral animals are predators on the larval stages of the starfish. Numerous examples of man's interference with the dynamic stability of ecosystems could be added to the above instances. It is evident that actions taken without examination of ecological relationships can lead to unfortunate and unanticipated problems in biological water pollution.

Salt spray may become a pollutant of the air, seriously affecting terrestrial vegetation or nearby fresh water sources. Yet, on the other hand, unforeseen changes may occur due to the lack of salts. At Back Bay, a national bird refuge in Virginia, many species of the genus *Potomageton*, a duck food source, became reduced to the point where migratory water fowl were no longer utilizing the area. It was discovered that fine, suspended silt from run-off of agricultural land was preventing germination of seeds by keeping light from reaching the seeds. Silt had formerly been precipitated through the influx of small amounts of salt water—up to about 12 parts per thousand; but the salt water was no longer reaching the area because all natural entrances of ocean water had been sealed off under the mistaken impression that no salts should be in the bay. Now ocean water is pumped into the refuge. However, if the salt content goes much higher than 12 parts per thousand then the success of large-mouth black bass egg hatching goes down rapidly.

Some species of plants and animals, although not harmful in themselves, may be indicators of pollution or of other undesirable changes in the environment. It is therefore desirable to monitor the presence of such species that serve as sentinels. Concentrations of phytoplankton and beds of attached water plants may be detected remotely, as may certain animal groups such as schools of fish, marine mammals, birds, and turtles. Studies are being conducted to establish characteristics of fish schools by multi-spectral photography, including reflectance spectra of individual fish and schools, and absorption spectra of fish oil films. Pulse-gated laser systems with image intensifiers are being used to detect bioluminescence. Black-and-white, color and color infrared films have also been used. Species separation by spectral analysis has been attempted. These methods might be adapted for detection of vertebrate nekton species as indicators.

Black-and-white and color film could be used extensively in aircraft for detection of plant cover on water surfaces (such as the water hyacinth) or for detecting many pelagic vertebrates that commonly inhabit the water surface. The absence, as well as the presence, of species can be considered as indicators.

Intimately involved with the biological pollution problem is the effect of pollutants on the very important borders of the world's bodies of water. These regions, commonly called the wetlands, are fragile ecosystems of great value to man. They are areas of high primary biomass productivity and, although we understand little regarding the paths taken by nutrients produced, there is general agreement that large populations of edible fish, shell fish, and animals are dependent upon wetlands for their existence. Man uses wetlands extensively for convenience and sport. Wetlands are included in this report on pollution because they are so gravely affected by many of man's activities and because only remote-sensing techniques can provide adequately broad reconnaissance.

For example, wetlands need to be mapped accurately and the distribution and seasonal changes of vegetation monitored. Since these areas are submerged or partly submerged, large-scale mapping by conventional land-based techniques becomes prohibitively time consuming. The wetlands require 10-meter resolution and should be mapped every 2 weeks to 3 months, depending on the season.

Bacteria

Water pollution is not necessarily confined in its effects to the aquatic habitat. There are examples of demonstrable relationships between air and water pollution. It has been shown that bacteria from the bottom as well as the water itself may be ejected into the atmosphere by bubbles of gas when they reach the surface and break (Blanchard and Syzdek, 1970). A reverse exchange is true also. The water supply of the city of Asheville, North Carolina, is considered polluted because of the fallout, so to speak, of bacteria from the air into the water.

The depletion of oxygen in the eutrophication process can produce a favorable medium for the development of certain *Clostridia* species that can be lethal to waterfowl and man. Many instances of food poisoning and duck kills have been ascribed to this cause.

Frequent monitoring of selected epidemiologically significant water bodies, with laboratory analyses to establish the population dynamics of the organism relative to the eutrophication processes, is recommended.

Red Tide

One of the more dramatic examples of a natural phenomenon that is exacerbated by man's pollution is the so-called red tide. This phenomenon is due to a great bloom of a minute organism (a dinoflagellate) that has a reddish color and imparts this color to the water. The presence of the organism in blooms can be quite toxic to fish and other organisms. The red tide characteristics that are of primary interest are species composition, concentration, distribution, movement, growth, and decay.

Concentration can best be inferred from the visible region spectral reflectance curve which shows absorptions due to pycobilin pigment and chlorophyll. The intensities of these spectral absorptions, as well as certain other features of these curves, serve to indicate the types and concentrations of the plankton in the surface layers of the water.

Dimensions and locations of the blooms should be known to approximately 100 meters, and should be monitored on approximately a daily basis to determine growth and decay, although to observe tidal effects on the positions of the blooms would require monitoring every 4 to 6 hours. There is every reason to expect that remote sensing will offer substantially more and better information about the characteristics of red tides than is currently available by means of surface measurements.

Human and Cultural Effects

Man's use, or misuse, of the land is one of the most important keys to our understanding of problems in the environment. As population and rate of change continue to accelerate, man's activities must be studied in terms of their effects on the environment. For example, sediment increases where lands are stripped for agriculture, new housing, or highways, or where lumbering practices are careless. Where vegetation is destroyed by herbicides, defoliants, discharge from ore processing operations, or smog, a large percentage of these toxic substances may be washed into nearby water bodies. As urban centers continue to expand and more and more land is covered with concrete, asphalt, and buildings, surface runoff increases and whole drainage systems are changed, thus affecting the estuaries, harbors, and bays into which they flow. As coastal lands are filled and dredged to provide space for man, fragile plant and animal communities are destroyed.

Land pollution problems are different from specific air and water problems because, with land, ownership is involved. Unlike air and water problems which drift or float away to become others' problems, land problems remain stationary. This factor, however, makes the remote monitoring of man's activities one of the most feasible things to be accomplished from space. To this end the use of ERTS and future spacecraft systems and programs should be accelerated.

INSTRUMENTATION FOR REMOTE SENSING OF WATER POLLUTION

The sensing of specific local instances of water pollution has been accomplished for many years from aircraft and/or boats through visual identification of the source and documentation of the scene on film by means of a camera. The last several years have seen a rapid evolution of instrumentation having high potential for regional and global pollution monitoring. The instrumentation includes (1) imaging scanners, capable of providing a view of the scene outside the spectral range of the human eye or any film emulsion, (2) imaging spectrometers, capable of rapid, detailed spectral analysis and mapping of the radiation (solar or thermal) leaving a water body, (3) correlation instruments, such as the Fraunhofer Line Discriminator or the Chlorophyll Correlation Radiometer, which are capable of eliminating the background signal through prior knowledge of unique spectral characteristics of the pollutant or its manifestation, (4) microwave radiometers and radar, which are capable of providing all-weather, day/night capability of detecting oil spills, (5) pulsed laser systems, which are potentially capable of remote, detailed analysis of individual pollutants through excitation and detection of their fluorescence characteristics, and (6) specialized instruments, such as low light level imagers and scintillation detectors which are capable of sensing bioluminescence and radioactivity.

These instruments can be used at various levels of a multistage sampling program whose components are satellite observations, detailed aircraft surveys, and *in-situ* monitoring and analyses at fixed stations. The synoptic capabilities of satellite instrumentation will be augmented by capabilities of other stages of observation and detection. Satellites (Nimbus and ERTS) possess the capability of interrogating daily, on a global basis, *in-situ* monitoring stations to obtain direct analyses of specific pollutants not amenable to remote sensing.

The following sections briefly describe the basic principles of 14 different types of instruments used in remote sensing. Table IV lists the instrumentation requirements for remote sensing of pollution and Table V shows the correspondence of the 14 instruments to specific applications in water pollution.

TABLE IV

INSTRUMENTATION REQUIREMENTS FOR REMOTE SENSING OF POLLUTION

An optimum value and an (acceptable value) are given for each entry.

N/A—not applicable

	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	SPECTRAL RANGE	TEMPORAL RESOLUTION	SOLAR ELEVATION	LOOK LOW ANGLE (FROM NADIR)	AREA COVERAGE
OIL	10-30m (300m)	Broad-band	UV, Vis. u wave	2-4 hrs. (1 day)	only important with glitter	only important with glitter	200x200km (20x20km)
SUSPENDED SED.	20m (500m)	.15um (.15um)	350-800nm (400-700nm)	2 hrs. (1 day)	45° (30°-60°)	0 to + 15° (− 5° to + 30°)	350x100km (10x10km)
CHEM. & TOX. WASTES	10m (200m)	.015um (.015um)	350-700nm (400-700nm)	5 hrs. (10 days)	45° (30°-60°)	0 to + 15° (− 5° to 30°)	35x35km (10x10km)
SOLID WASTES	10m (200m)	.015um (.015um)	350-800nm (400-700nm)	5 hrs. (10 days)	45° (30°-60°)	0 to + 15° (− 5° to + 30°)	35x35km (10x10km)
THERMAL EFFLUENTS	30m (500m)	± 0.2°C (± 1°C)	10-12um (10-14um)	2 hrs. (10 days)	N/A	to be determined	35x35km (10-10km)
RADIOACTIVE WASTES	30m (500m)	N/A	gamma (gamma)	5 hrs. (15 days)	N/A	0° (0°)	35x35km (10x10km)
NUTRIENT WASTES	100m (2km)	.005um (.015um)	400-700nm (400-700nm)	2 days (14 days)	45° (30°-60°)	0to + 15° (0to + 30°)	350-350km (35x35km)
INTRO. OF SPECIES	to be determined	.1um (.1um)	Vis. (Vis.)	3 mos. (1 yr.)	N/A	N/A	350x350km (10x10km)
RED TIDE	(2km)	.015um (.015um)	400-700nm (400-700nm)	5 hrs. (2 days)	45° (30°-60°)	0to15° (− 5° to + 30°)	350x35km (20x100km)
HUMAN & CUL. EFFECTS	10m (100m)	Variable	UV, Vis., IR,u wave	1 yr. (5 yrs.)	N/A	N/A	350x350km (35x35km)

TABLE V

SENSOR/APPLICATION CORRESPONDENCE FOR REMOTE SENSING OF POLLUTION

1—PRESENTLY AVAILABLE
2—UNDER DEVELOPMENT
3—POTENTIAL APPLICATION

*—WITH INFRARED CHANNEL

			FILM CAMERAS												
		U/V	COLOR	COLOR I/R	MULTISPECTRAL	MULTICHANNEL SCANNING RADIOMETER	CORRELATION RADIOMETER	FRAUNHOFER LINE DISCRIMINATOR	PULSED LASER SYSTEM	LOW LIGHT LEVEL DEVICES	I/R IMAGER-SCANNER	MICROWAVE RADIOMETER	RADAR	SCINTILLATION DETECTOR	POLARIMETER
OIL		1	2	3	1	1	1	1	1		2	1	1		1
SUSPENDED SEDIMENT			1	1	1	1	2		2						2
CHEM. & TOXIC WASTES			2	3	2	2	2	3	2						
SOLID WASTES			1	1	1	1	2		2						2
THERMAL EFFLUENTS						1*					1	1			
RADIOACTIVE WASTES														1	
NUTRIENT WASTES			1		1	1	1		2						3
LIVING ORGANISMS	INTRO. OF SPECIES		2		2	2				3					
	BACTERIA								3						
	RED TIDE		1	1	1	1	1		1						
	HUMAN & CUL. EFF.		1	1	1	1				1	1		1		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14

INSTRUMENT: *CAMERA*

Number: 1, 2, & 3 (These numbers correspond to the numbers shown along the bottom line of Table V.)

Description: Photography is undoubtedly the most commonly used remote sensor technique in detection and documentation of water pollution. The photographic spectrum encompasses the wavelength region from 350 to 1200 nm, while the visible spectrum extends from 400 to 700 nm. It is possible, through the use of filters and the selection of film having the proper spectral sensitivity, to isolate a specific spectral region in which the reflection spectrum of the pollutant is most characteristic and/or most pronounced. It is possible to detect, by analyzing the resulting photographs, subtle tone patterns associated with nutrient, chemical, and toxic wastes (Scherz, 1967; Scherz, Graff, and Boyle, 1969), sediment in turbid waters (Lebley, 1968), and oil on the water surface (Mundary and Penney, 1971). The most common photographic methods for water pollution detection utilize ultraviolet ($<$400 nm), color (Ektachrome), and color infrared (Kodak IR Ektachrome 8443) photography.

Spectral Range: 350 to 1200 nm

Spectral Resolution: 50 nm (average)

Spatial Resolution: 20 m (spacecraft)

Status: Experimental aboard manned spacecraft. Operational aboard aircraft.

Application References: Scherz, 1967; Scherz, Graff, and Boyle, 1969.

INSTRUMENT: *MULTIBAND CAMERA SYSTEM*

Number: 4

Description: A multi-lens camera system or a multi-camera system capable of simultaneously recording four separate images, each in a different spectral band. Each lens or camera has a filter which passes only a selected portion of the incident spectrum. Each image thus represents the characteristic reflectance of the water body in the corresponding spectral region. The images can be viewed

separately or in registration to produce conventional color, color infrared, or false color photographs.
Spectral Range: 380 to 1000 nm
Spectral Resolution: 50 - 300 nm
Spatial Resolution: 20 m
Status: Multi-camera system already flown aboard manned spacecraft. Has been flown operationally aboard aircraft.
Application References: Mundary and Penney, 1971; Lebley, 1968; Scherz, Graff and Boyle, 1969; Stilwell, 1969.

INSTRUMENT: *MULTICHANNEL SCANNING RADIOMETER (OBJECT PLANE SCANNER)*
Number: 5a
Description: This type of instrument is commonly referred to as a multispectral optical-mechanical scanning radiometer. A mirror scans a swath on the earth's surface cross-track to the vehicle flight vector. After focusing, the collected radiation is dispersed by a prism or grating and each of several wavelengths is directed to a separate detector. It is capable of high resolution and offers the advantage of making simultaneous, well registered measurements of ultraviolet, visible, and infrared (both reflected and emitted). This instrument is recommended for certain oceanographic applications near shore and for most applications in rivers, harbors, and estuaries where high resolution is required in conjunction with spatial registration between color and temperature measurements.
Spectral Range: 0.32 to 20 μm
Spectral Resolution: 20 - 100 nm (visible)
Spatial Resolution: 0.07 - 2 mrad (visible)
Status: Versions of this instrument with from 4 to 24 channels are ucrrently under development.

No. of channels	Developer	Application
4/5	NASA/Hughes	ERTS A/B
10	NASA/Honeywell	Skylab
24	NASA/Bendix	C-130 aircraft

INSTRUMENT: *MULTICHANNEL SCANNING RADIOMETER (IMAGE PLANE SCANNER)*

Number: 5b

Description: This type of instrument utilizes high quality spectrometer optics to generate a single image containing a series of spectral signatures from each point in a line cross track to the vehicle flight vector. The array of spectra is read out by a television-type camera. It has no moving parts and gives excellent registration between all bands in the reflectance spectrum covered (0.4 to 0.85 μm). It can also operate in either of two modes, giving high ground resolution with moderate spectral resolution, or low ground resolution with high spectral resolution. Either multispectral images or an array of spectral signatures may be obtained from the output signal. It can supply the high spectral resolution and low NEΔP required for some oceanographic applications.

Spectral Range: 0.4 to 0.85 μm

Spectral Resolution: 7.5 - 37.5 nm

Spatial Resolution: 0.12 - 30 mrad

Status:

No. of channels	Developer	Application
60/12 (selectable)	NASA/TRW	RB-57F aircraft
20	NASA/TRW	AAFE program

INSTRUMENT: *CHLOROPHYLL CORRELATION RADIOMETER*

Number: 6

Description: An instrument that gives a real-time measurement of chlorophyll concentration within the range 0.03 to 20 mg/m^3. The technique utilizes a differential radiometer to continuously compare the intensity of upwelling sunlight at a sample wavelength (443 nm), located at the absorption maximum of phytoplankton, to the intensity at a reference wavelength (525 nm) located at the absorption minimum. Changes in light intensity, variations in water surface roughness, or scattering within the water body have similar effects on the intensities at both wavelengths and are automatically corrected. Variations in the concentration of phytoplankton, however, primarily affect the intensity at the sample wavelength, resulting in a signal output which is proportional to the apparent absorption band strength. Atmospheric effects must be evaluated before the instrument can be utilized on board a satellite.

Spectral Range: 443 nm and 525 nm

Spectral Resolution: 15 nm

Spatial Resolution: 10 - 200 mrad

Status: Has been flown experimentally aboard aircraft.

Application References: Arvesen and Weaver, 1971; Arvesen, Millard and Weaver, 1971.

INSTRUMENT: *FRAUNHOFER LINE DISCRIMINATOR*

Number: 7

Description: Fraunhofer lines are dark lines in the solar spectrum caused by selective absorption of light by gases in the "reversing layer" at the base of the solar atmosphere. Widths range from less than 0.01 nm to a few tenths nm, and the central intensity of some lines is less than 10 percent of the adjacent continuum. The lines are sharpest, deepest, and most numerous in the near ultraviolet, visible, and near infrared regions of the spectrum.

The Fraunhofer line-depth method involves observing a selected Fraunhofer line in the solar spectrum, and measuring the ratio of the central intensity to the intensity at a convenient point on the continuum a few tenths of a nm distant. This ratio is compared with that for the reflection spectrum of a surface that is suspected to luminesce. The two ratios normally are identical, but luminescence is indicated where the ratio for the reflection spectrum exceeds that for the solar spectrum. The instrument is not line scanning.

Spectral Range: Ultraviolet to near infrared

Spectral Resolution: approximately 0.05 nm

Spatial Resolution: N/A

Status: Has been developed by USGS/NASA/Perkin-Elmer.

Application Reference: Hemphill, Stoertz and Markle, 1969.

INSTRUMENT: *PULSED LASER SYSTEM*

Number: 8

Description: A pulsed laser with a high-speed detection system for viewing either the return of the transmitted pulse or the induced fluorescence emission from the water surface or water body. By using a pulsed (3 nsec) blue-green (neon) laser, and viewing the return from the surface of the water and the return from the water bottom, a remote measurement of water depth was performed to an accuracy of 0.5 m (Hickman and Hogg, 1969; Hickman, 1969). By using an ultraviolet pulsed laser, it is possible to excite fluorescence in oil films (Fantasic, Hard, and Ingroo, 1971), chlorophyll a, and rhodamine B dye (Hickman and Moore, 1970). The detection system, in this application, is filtered to pass only the spectral region associated with the fluorescence and to block the wavelength of the excitation pulse.

Spectral Range: Variable

Spectral Resolution (Excitation): approximately 0.01 nm

Spatial Resolution: N/A

Status: Bathymetric system has been flown aboard aircraft. Fluorescence systems have been successfully operated in the laboratory.

Application References: Hickman and Hogg, 1969.

INSTRUMENT: *LOW LIGHT LEVEL DEVICES*

Number: 9

Description: These devices are capable of generating images at extremely low light levels ($< 10^{-3}$ lumen/m^2) and as such are useful for enhancing the brightness of bioluminescence caused by mechanical agitation of plankton when viewed at night. The output may be viewed in real time with an intensifier-telescope or with a low-light-level television system (with which it could also be recorded).

Spectral Range: Variable

Spectral Resolution: Broadband (visible/near infrared)

Spatial Resolution: $<$ 0.3 mrad

Status: A great variety of these devices have been developed by organizations like GE, Westinghouse, RCA, Dalmo-Victor, MIT, Hughes, and ITT.

INSTRUMENT: *INFRARED IMAGER/SCANNER*

Number: 10

Description: This instrument utilizes a rotating mirror or prism to scan a line cross track to the vehicle flight vector.

The infrared radiation is sensed by a cooled detector such as mercury cadmium telluride, mercury-doped germanium, or indium antimonide. The signal from the detector, after amplification, is used to modulate a lamp whose intensity is then recorded on a moving film synchronized with the rotating optics. Depending on detector type, these instruments operate in either the 3 - 5 μm or the 8 - 12 μm atmospheric window. The 8 - 12 μm window tends to be preferable because water bodies have their peak infrared emission in this region.

Spectral Range: 3 to 12 μm

Spectral Resolution: N/A

Spatial Resolution: Typical 1.5 - 4 mrad

Status: Many units have been developed by Bendix, Texas Instruments, TRW Systems, Hughes, Autonetics, HRB-Singer.

Application References: Proceedings of the International Symposia on Remote Sensing of Environment, University of Michigan, 1964 - 1971.

INSTRUMENT: *MICROWAVE RADIOMETER*

Number: 11

Description: Superheterodyne circuits and special switching techniques make the microwave radiometer a very sensitive instrument. The thermal emission of most sources in the microwave region usually varies linearly with temperature rather than with the 4th power of the temperature as in the infrared region. Hence, a microwave measurement of energy or "brightness temperature" is as sensitive to the emissivity of the object as to the temperature, which is not true for infrared measurements.

Frequency Range: 1 GHz to 37 GHz

Spectral Resolution: Broadband detection

Spatial Resolution: 20 - 200 mrad

Status: Microwave radiometers have been flown experimentally on aircraft in the above frequency range (except C-band (3.9-6.2 GHz)). 19.3 GHz and 37 GHz imaging radiometers will be flown in the Nimbus series of satellites.

INSTRUMENT: *RADAR IMAGER*

Number: 12

Description: Pulsed energy in the microwave region is transmitted and received from an appropriate antenna system. The pulse length, antenna size, and data processing primarily determine the spatial resolution, with short pulses, large antennas, and sophisticated processing required for high spatial resolution. If the radar technique measures only the amount of energy returned to the antenna the instrument is frequently called a scatterometer. If the radar creates images with a side-looking antenna array on an aircraft or satellite it is called a side-looking airborne radar (SLAR). If increased data processing is used to improve spatial resolution over that provided by the antenna, the radar is called a synthetic aperture radar (SAR).

Frequency Range: 1 GHz to 35 GHz

Spatial Resolution: $<$ 1 m from aircraft

Status: Many aircraft systems have been flown. Skylab will have a combined radiometer/scatterometer system.

INSTRUMENT: *SCINTILLATION DETECTOR*

Number: 13

Description: A gamma-radiation-sensitive phosphor is located adjacent to a photo-multiplier tube, which feeds a scintillation integrator circuit. Intensities as low as 0.005 mrads per hour can be measured. The method may be effective up to altitudes of the order of 150 meters.

Spectral Resolution: Broadband (gamma)

Spatial Resolution: $<$ 2 rad

Status: Has been flown over the site of an underwater nuclear detonation. U.S. Geological Survey studies have been conducted over Columbia River and have disclosed anomalous aeroradioactivity.

INSTRUMENT: *POLARIMETER*

Number: 14

Description: An instrument capable of measuring the intensities of the two perpendicularly polarized components of the radiation reflected and backscattered from a water body. The measurement is usually performed at the Brewster angle (approx. 0.93 radians for water), where there is a reflection minimum in the component polarized parallel to the plane of incidence. By filtering out the normal-polarization component of light the instrument views primarily radiation backscattered from below the water surface. Measurement of the difference in intensity between the two polarized components at any angle yields information primarily representative of water surface characteristics. The first method can be used to help measure turbidity (Halajian and Hallock, 1971) and to reduce the influence of reflected skylight on the measurement of water color (Clarke, Ewing, and Lorenzen, 1970). The second method can be utilized to advantage in the detection of oil spills (Millard and Arvesen, 1971).

Spectral Range: Variable

Spectral Resolution: 50 - 100 nm

Spatial Resolution: 3 m (aircraft)

Status: Experimental use aboard aircraft.

Application References: Halajian and Hallock, 1971; Millard and Arvesen, 1971; Clarke, Ewing, and Lorenzen, 1970.

RECOMMENDATIONS

1. This Panel recommends an acceleration of research related to the application of remote sensing techniques to the special problem of water pollution. Applicable biological disciplines should be given an important role in this work.
2. We believe that an assemblage composed of *in-situ* fixed or drifting stations, aircraft, balloons, and satellites will provide the most economical and effective overall method for the detection and quantitative monitoring of water pollution. In this multiplex system, the function of spacecraft should be dominant.
3. Because of the complex interrelations of the natural world, this Panel recommends that the particular problems arising from pollution be studied in the context of the total environment in which they are embedded.
4. The systems evolved should and can be multipurpose, adapted to the needs of agricultural, atmospheric, and oceanic users. Such commonality must, however, be real and mutual, with no special use allowed to degrade the effective-

ness of the system for some other use.

5. In order to provide for an orderly and rapid advance in this field, NASA should now design and implement a Prototype Operational Environmental Monitoring System. Such a prototype system would extend at least over the entire United States and nearby ocean and should be intimately responsive to the needs of regional activities and adapted to the solution of special problems that exist in particular areas of the country.

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SECTION IV

PARTICLES IN THE ATMOSPHERE

H. Blau, Jr.
***C. Byvik
R. Fraser
G. Grams
T. Haig
F. Harris
B. Herman
***A. Holland
J. Lawrence, Jr.
W. Matthews
**S. Melfi
G. Robinson
Z. Sekera
*V. Suomi

*Chairman of Panel
**Associate Chairman
***Assistant Chairman

SECTION IV

PARTICLES IN THE ATMOSPHERE

INTRODUCTION

Atmospheric particulate matter has important climatic, biological, and economic effects which range from local to global in scale. It is responsible for the costly soiling of materials, buildings, and textiles (Barrett and Waddell, 1970; Amer. Assoc. Advancement Sci., 1965), and is an important factor in accelerating the corrosion of steel and zinc. Biologically, high concentrations of particles can lead to an increase in respiratory illnesses and in the death rate in man and animals. The particulate matter may stunt plant growth, interfere with pollination, make the plant more susceptible to pathogens and, if the dust contains a soluble toxicant, may directly damage the plant (Nat. Air Pollution Control Admin., 1969). Barrett and Waddell (1970) have estimated the national total cost of air pollution for the year 1968 at over $16 billion, of which almost $6 billion is due to particles.

The presence of an increased number of hygroscopic sulfate and nitrate particles (Junge and Schleich, 1969) leads to increased acidification of precipitation. According to Oden the acidity of precipitation affects the soil, forests, and fish (Oden, 1968). Organisms normally cannot exist in highly acid water ($pH < 4.0$). Salmon cannot spawn at $pH < 5.5$ The study by Oden shows the importance of measuring not only the particulate matter and formation forerunners, but also their transport in order to determine the trajectory and locate the source. There are indications that the acidity of precipitation in the Northeastern United States is increasing.

In recent years scientists have become increasingly aware of the need for intensive studies of the role of particles in the transfer of solar and terrestrial radiation through the earth's atmosphere. The importance of this problem has been emphasized in recent summaries (Summary Atmos. Radiation Work Study Conf., 1970; Summary of Findings of Workshop on Bomex Radiation and Particulate Investigations, 1970; Frisken, 1971; Landsberg, 1970; Mitchell, 1971; Robinson, 1970; Singer, 1970) in which the radiational characteristics of particles was given the highest priority among the problems requiring additional research effort.

Particles affect the transfer of radiation through the atmosphere by virtue of their ability to absorb, emit, and scatter radiation. In the visible portion of the spectrum, the scattering of radiation by particles can equal or exceed the scattering due to the normal gaseous constituents. In some cities the long-term average of solar radiation reaching the ground is reduced by particles by more than 10%. The most recent evidence of the absorption of solar energy by atmospheric particles has been reported by a group in the Soviet Union in their Complex Atmospheric Energetics Experiment. The Barbados Oceanographic and Meteorological Experiment (BOMEX) investigation of radiation and particulate matter in the tropics indicates that 25-100% more absorption of solar energy in the lowest $3x10^4$ N/m^2 (300mb) of the atmosphere is occurring than would be expected based on calculations assuming a gaseous atmosphere alone.

The interactions of aerosols with solar radiation may change the global albedo. The direction, increase or decrease, of a possible albedo change depends upon the optical properties of the particles and of the underlying surface. Any change of global albedo must lead to a change in the mean temperature of the planet earth; that is, to a change in the climate. Thus, there is a growing concern to monitor the earth's albedo.

The two experiments referred to above indicate that appreciable absorption and emission of infrared radiation from particles must also be taking place. Results from BOMEX indicate that the observed downward infrared flux is consistently greater than computed, and it is suspected that the discrepancies are due to the presence of particles. These experiments and numerous previous measurements present strong evidence that particles play an important role in the transfer of radiation. Their true role is difficult to assess because of a lack of knowledge both of their spatial and temporal distributions and of their optical properties. Although considerable progress has been made in the computations of the transfer properties of a turbid atmosphere in the visible region, and in the evaluation of the aerosol effect in the infrared region (Herman and Browning, 1965; Herman, Browning, and Curran, 1971; Hansen, 1969; Kattawar and Plass, 1967, 1968; Dave and Gazdag, 1970; Peterson and Bryson, 1968), it seems that our biggest problem in understanding the role of particles in radiative transfer is a lack of sufficient knowledge of the properties of the particles themselves. Thus, what is required is a detailed knowledge of the size, shape, concentration, and composition of the aerosols and their optical properties, as well as knowledge of their spatial and temporal distribution. Spatial distributions of global dimensions can be obtained only by remote sensing from space platforms. The other parameters may be obtained by direct sampling and laboratory studies, but the effort here needs to be increased.

A distinction should be made between natural particulate matter, and that which is man-made. The atmosphere contains a background level of particulate matter which plays an important part in the radiation budget of the earth-atmosphere system. Man-made contributions, superimposed on the natural background, may alter this budget and cause a change in climate on a local, or possibly a global scale.

To assess the effects of the man-made (pollutant) portion, determinations must be made of both the natural and man-made contributions. This is much more difficult than may appear at first glance. There is little doubt that over many populated areas, atmospheric turbidity is increasing. Solar radiation measurements in Japan and in the European part of the USSR show this increase clearly. However, very few long-time records of atmospheric turbidity are available from regions far enough removed from local sources of pollution to give a representative picture of global turbidity. One such record, from Mauna Loa Observatory, Hawaii, dates back to 1957. Analysis of these data up to 1968 (Peterson and Bryson, 1968) indicates a long-term increase in turbidity. A later analysis (Ellis and Pueschel, 1971) of these data through 1970 showed that the Mauna Loa turbidity has recovered nearly to its 1957 level and that, on a global scale, it is probable that natural aerosols are the prime contributor to global atmospheric turbidity. Best current estimates are that man-made particles comprise 5-10% of the global particle loading, although values up to 45% may be found in the literature (SMIC, 1971).

Clearly, it is important that a world-wide monitoring system be established as soon as possible so that future changes may be recognized promptly. Remote sensing may provide the basis for this system.

Measurements of particulate matter are needed in the construction and testing of mathematical models that describe the growth, transport, and decay of aerosols over local, regional, or global scales. Such models can be invaluable to those who must predict and control pollution in large cities or state-wide areas by enforcing restrictions on the quality and quantity of fuels used by industries and power plants. Global models will be needed increasingly to assess the direction and magnitude of climatic change that might be due to man's activities.

In the remainder of this section, we shall point out some of the more pressing problems in this area and some steps that we feel can and should be implemented now and in the future.

In the preceding discussion we have outlined the significance of particulate matter as a pollutant, both in causing local and regional harm and in affecting the global heat balance. In the following we have provided a more thorough review of the problem, especially with regard to remote measurement of particulate matter and its effects. The origins, reactions, and transport of various types of particles are first discussed. Then an outline is given of the basic theory of radiative transfer in the atmosphere, especially as affected by suspended matter. The final section considers in greater detail the possibilities for remotely monitoring, by optical means, the make-up of aerosols and their effects. Considerable discussion of earth-albedo measurements is included. Suggested directions for the development of appropriate instrumentation are also indicated.

ATMOSPHERIC PARTICLES

In order to better understand and predict what particles do in the atmosphere we must better understand their life-cycle. The life-cycle of a particle in the atmosphere, that is, the period between its introduction into and its disappearance from the atmosphere, may be long and complicated. A particle in the atmosphere may have its origins in the evaporation of water droplets, condensation of vapor, chemical reactions that evolve into macromolecules, meteoroids from space, and the earth itself. They may leave the atmosphere by evaporation, chemical reactions, sedimentation, or rainout. In the atmosphere, the particles are subjected to a multitude of influences, for example, thermal, gravitational, magnetic, electric, electromagnetic, and chemical, which affect their lifetimes. One can either observe the particle interactions directly or monitor key atmospheric constituents and environmental factors and postulate the interactions from previous knowledge.

SOURCES

Mason (1962) classifies the mechanisms of formation of aerosols into the following general categories: 1) the condensation and sublimation of vapor and the formation of smoke by both natural processes and those associated with man's activities, 2) chemical reactions involving trace gases in the atmosphere, 3) the mechanical disruption and dispersal of matter at the earth's surface, 4) the coagulation of very small particles to form large particles which can thereby be of a highly mixed composition, and 5) extra-terrestrial matter, which is of small importance. Figure 1 gives the sizes of typical airborne solids (Hidy and Brock, 1970). The sizes of most particles of interest lie within the range 0.1 to 20 μm.

Combustion products are the principal sources of particles. Urban sources are well-known. Increased efforts being made to prevent industrial combustion products from escaping into the atmosphere are only partially successful, as the finer particles with longer potential life still escape into the atmosphere. Less well-known is the fact that agricultural burning is a major source of particles in many parts of the world. Agricultural practices are also responsible for some of the soil particles that are presently abundant in the at-

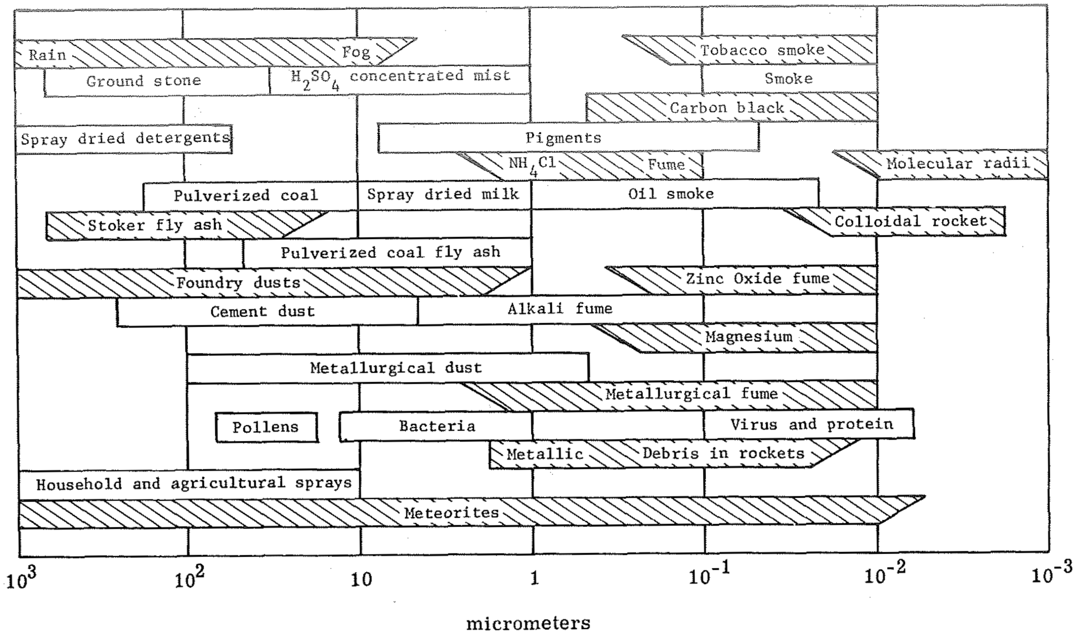

Figure 1.- Size range of atmospheric particles. (From Hidy and Brock, 1970.)

mosphere. Wind-raised dust is a direct consequence of such practices as overgrazing and cultivation in semi-arid areas. The American dust-bowl of the 1930's was a dramatic manifestation of improper farming.

Particles are produced from atmospheric gases, but the physics and chemistry are often poorly understood (Mohnen and Lodge, 1969; Wilson, Merryman, and Levy, 1969; Vohra and Nair, 1970; Mueller and Imaga, 1970). Sulfate particles are produced from SO_2, which is both a pollutant and a natural gas, and smog particles are a result of automotive emission.

Turning from anthropogenic to natural particle sources, one can begin with soils, since they supply the largest fraction of the total mass of atmospheric particles (Andrew and Lavrinenko, 1968; Shedlovsky, 1970; Gillette, 1971). Of course, strong winds over loose soil will raise dust, but even gentle breezes are effective. Soil particles are sufficiently pervasive through the atmosphere to constitute a significant fraction of particles even in industrial environments (Cadle, 1966).

Other important sources of natural particles are forest and grass fires, volcanoes, and sea spray. These particles are the predominant condensation nuclei of clouds (Mason, 1957; Hallett, Orville, Sartor, and Weickmann, 1971). Just as particles are formed from pollutant gases, they are also formed from natural gases. In the stratosphere, particles are formed from H_2S of biological origin and from SO_2 and H_2S emitted by volcanoes. Another example is the blue haze seen above forests, which forms from terpenes emitted by the vegetation. The extent of particle formation from gases is not known.

The optical properties of some aerosols are changed by the process of condensation of water vapor on them. Therefore, remote sensing experiments must allow for these significant effects in order to derive information concerning particles. Neither the optical effects caused by condensation, nor the condensation-evaporation processes are completely understood for the numerous types of particles found in the atmosphere.

INTERACTIONS

The atmospheric aerosol may be considerably modified from its original form with the passage of time. The major processes that modify the aerosol include coagulation, sedimentation, rainout, and attachment (to leaves, etc.). Other processes may involve chemical reactions, interactions with clouds, and miscellaneous particle interactions. Generally speaking, these processes tend to reduce the number of very small and very large particles, with the various particle interactions tending to produce a frequency distribution of particle sizes having a maximum in the radius interval 0.1 to 1 μm. The coagulation of small particles is the major effect determining the lower limit of particle sizes during the time evolution of the particle size spectrum of the atmospheric aerosol. A comprehensive review of the theory of coagulation, by Drake, provides details of the mathematical treatment of this problem.

Junge (1963) performed numerical calculations on the effects of coagulation for a distribution function following typical natural sizes. The result is presented in Figure 2. It is clear that particles having sizes less than 0.1 μm have individual lives that are very short in comparison to meteorological time scales. While the example may not be necessarily representative of the normal size distribution function, it does illustrate that after a relatively short time particles less than 0.1 μm radius will coagulate and form larger particles while the effect of coagulation on particles larger than 0.1 μm is much slower.

While coagulation plays a key role in determining the lower limit of the aerosol spectrum, sedimentation is the major process controlling the upper size limit (Junge, 1963; Hidy, 1971). Two theoretical formulations of settling velocity are available. One, derived from kinetic theory, applies to molecular sizes; the other is the Stokes-Cunningham formula for larger particle sizes. The expressions for settling velocity give identical results in intermediate size ranges (between 10^{-3} μm and 10^{-2} μm for a pressure of one atmos-

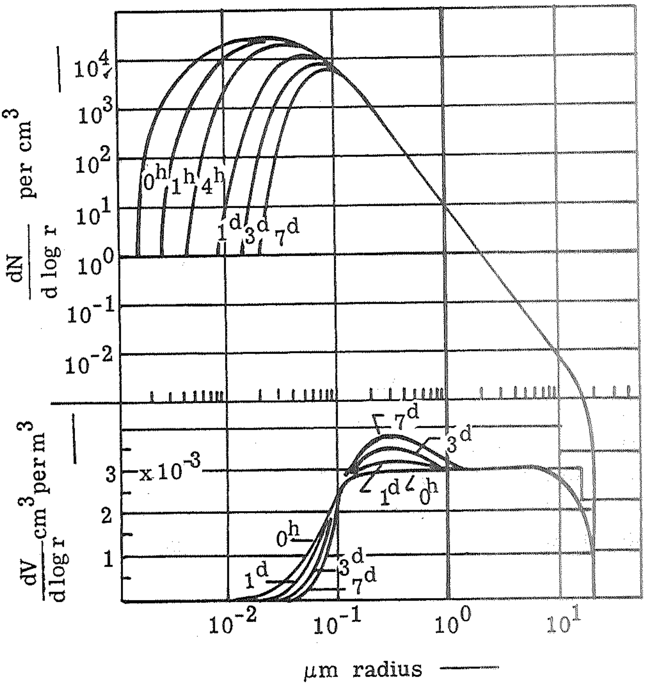

Figure 2.- Calculated change in the size and volume distribution of continental aerosols due to coagulation. (From June, 1963) h = hours, d = days, V = volume of particle in a cubic meter of air, N = number of particles in a cubic centimeter of air.

phere, the upper limit increasing with altitude). By proper application of these formulas, settling velocities for the entire spectrum of aerosol sizes can be obtained. Junge has shown that the effect of gravitational sedimentation can be neglected for particles having radii less than 1 μm. His results also confirm the tendency to establish a practical upper limit to the size distribution of the order of 10 μm radius.

SINKS

Particulate matter is removed from the atmosphere through rainout, washout, and dry deposition. Rainout is the process whereby droplets form around freezing and condensation nuclei and then fall as rain or snow. Washout is the collection and removal from the atmosphere of particulate matter by falling raindrops or snowflakes. Estimates of the effect of these processes on the removal of particulate matter require measurements of the available freezing and condensation nuclei, and the amount, intensity, drop size distribution, and chemical composition of precipitation. More detailed information can be found in SCEP (1970) and Amer. Chem. Soc. (1969, 1971). Figure 3, taken from Yamamoto, Tanaka, and Arco (1968), illustrates the effectiveness of precipitation in removing aerosols. A washout effect is also apparent in the aerosol particle size spectra observed by Carnuth and Reiter (1966). Reiter (1971) points out that chemical analyses of the soluble material washed out in rain indicates that this material is primarily continental in origin. He also cites evidence for industrial origin of some washed-out material.

DISTRIBUTION PROCESSES

Distribution processes transfer the particulate matter from its source, or origin, to the location where it leaves the atmosphere. However, information concerning these processes is fragmentary. Knowledge of the emission, transformation, transport and diffusion, and removal phases of the airborne particulate cycle would be required to establish an understanding of the global distribution of particulate

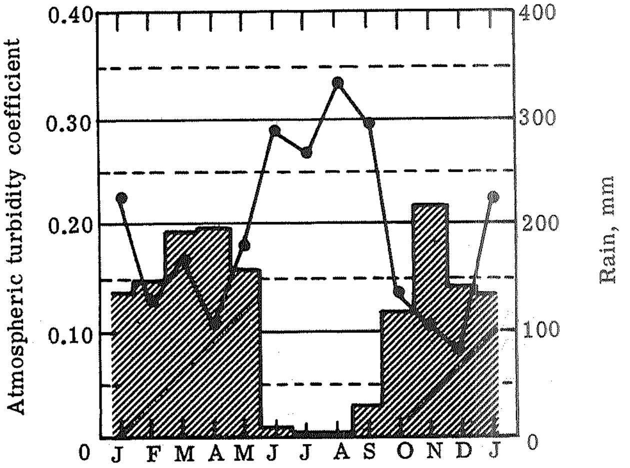

Figure 3.- The relation between the monthly average value of the atmospheric turbidity coefficient (●) and monthly amounts of precipitation (histogram) for Leopoldville-Binza.

(From Yamamoto, Tanaka, and Arco, 1968)

matter in the atmosphere. Many questions need to be answered, including the time required to establish the observed distribution, the interchange of material between the hemispheres, the exchange between the various atmospheric layers such as the stratosphere and troposphere (perhaps also between the planetary boundary layer and the remainder of the troposphere), and the variation of particle content with air mass type and origin.

A global measurement program, as might be performed using techniques outlined in the section entitled "Remote Methods of Measurement," is required to gain insight into the above problems.

PARTICULATE POLLUTION OF THE STRATOSPHERE, A SPECIAL PROBLEM

The principal sources of atmospheric pollution are in the troposphere and it is natural that we look here for their effects. There is evidence, however, that the stratosphere may be even more sensitive than the troposphere to the effects of both man-made and "natural" pollution. In addition, the residence time of most pollutants is of the order of years in the stratosphere, as compared to days or weeks in the troposphere.

The presence of a layer of particulate material in the lower stratosphere was first deduced from observations of the purple light (Gruner and Kleinert, 1927; Gruner, 1942), a purplish glow that appears in the western sky during twilight.

The existence of such a layer was verified with particle sampling equipment carried on high-altitude balloons (Junge, Chagnon, and Manson, 1961; Chagnon and Junge, 1961). Vertical profiles of particle concentration obtained with an inertial impactor designed to collect particles larger than about $0.1\,\mu m$ radius persistently exhibited a broad maximum in particle concentration at about 20 km altitude (see Fig. 4, taken from Chagnon and Junge, 1961). Supplementary data collected by impactors on U-2 aircraft at 20 km (Friend, Feely, Krey, et al., 1961; Junge and Manson, 1961), in 1961, showed that particle concentrations between 60°S and 70°N exhibited little systematic latitudinal varia-

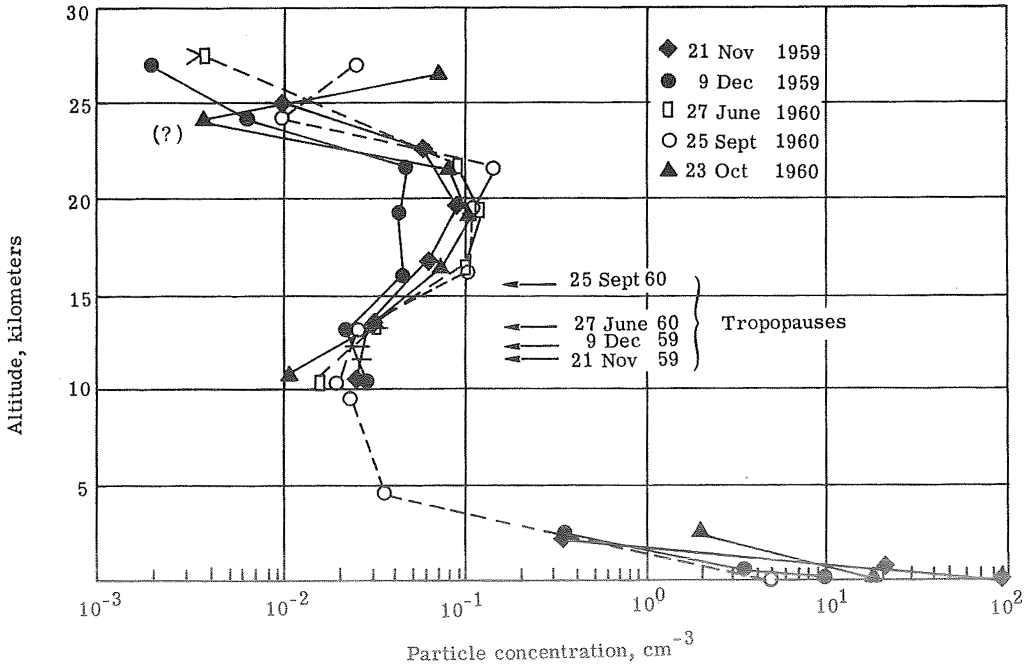

Figure 4.- Vertical distribution of stratospheric particles collected by inertial impactors, according to Chagnon and Junge (1961). Tropospheric measurements of other investigators are included for comparison.

tion and that the aerosol layer was indeed a world-wide feature of the lower stratosphere.

Chemical analyses of the particles collected by the impactors indicated that the majority of the particles were composed of sulfates (Junge, Chagnon, and Manson, 1961; Friend, Feely, Krey, et al., 1961). The chemical composition of the particles and the observed shape of the concentration profiles suggest that the particles are formed *in situ* by oxidation of traces of gaseous sulfur compounds (hydrogen sulfide and sulfur dioxide) that had entered the stratosphere by vertical mixing processes (Junge, 1963; Cadle, 1963; Fischer, Lodge, Pate, and Cadle, 1969).

Because of the great static stability of the stratosphere, particulate loadings can be drastically altered by volcanic eruptions. The eruption of the Mount Agung volcano on Bali (8.4° S, 115° E) on 17 March 1963 increased the aerosol content of the stratosphere and enhanced many of the phenomena that are associated with the presence of the dust layer. Some quantitative measurements of the increase of stratospheric aerosol concentrations before and after the Agung eruption using the same method of observation are available; they indicate that the aerosol concentration may have exceeded that of the ordinary sulfate layer by a factor of 20 during winter 1963-64 (Volz, 1969).

Remote sensing techniques have already been applied to the study of the stratospheric aerosol. During 1964 and 1965, a laser radar system was used to obtain information on the average characteristics and temporal variations of the vertical distribution of stratospheric aerosols (Grams and Fiocco, 1967). These data consistently showed a maximum in the relative concentration of aerosols between 15 and 20 km altitude. The study was conducted during the period when the aerosol layer was perturbed from its normal state by the Mount Agung eruption. The observed return from the layer was approximately 1.9 times the molecular return at College, Alaska.

Subsequent laser radar studies consistently determined scattering ratios having approximately the same magnitude as the 1964 and 1965 measurements until the summer of 1970. At that time, the backscattered laser echoes by particles observed with the National Center for Atmosphere Research (NCAR) laser radar system decreased by almost an order of magnitude. This substantial decrease in the aerosol content of the stratosphere has subsequently been confirmed by particle collections taken by NCAR in the stratospheric sampling program.

Attempts have been made to assess supersonic transport (SST) effects in terms of the dust clouds produced by the Agung eruption, which appears to have produced measured short-term increases in the temperature of the tropical atmosphere of 6°-7° and longer term (2-3 years) increases of 2°-3°. Comparisons with SST emissions may be suspect, however, because the volcanic eruption took place in the tropics and affected a very thick layer of the stratosphere and troposphere, whereas SST emissions will be injected predominantly at middle and high latitudes and will probably affect only a relatively thin layer of the stratosphere. However, our understanding of the full effects and removal rates of particles in the stratosphere fall short of what is needed to be able to predict the consequences of artificial injection of additional particles.

With additional information on the global distribution of dust concentrations, the needed better understanding of the behavior of dust in the stratosphere seems well within our reach. The section entitled "Remote Methods of Measurement" tells how this may be done.

RADIATIVE TRANSFER PROBLEM

Detection of airborne particles can range from the simple event of having one lodge in an eye through complex and sophisticated sampling techniques including microscopic and chemical analyses. Such sophisticated schemes are almost certainly restricted to point or local samples and require a considerable amount of skill. However, if we intend to use remote means of detecting particulate matter, we are forced to rely on the scattering of electromagnetic energy by the particles themselves. We are in fact dealing with the classical problem of radiative transfer through a turbid medium.

In principle we seek to infer the structure of an unknown medium by examining the radiation scattered or emitted by the medium as a function of the direction of the incident radiation, its intensity, polarization, and wave length. In general, classical transfer theory allows us to predict the energy transmitted or reflected by a plane-parallel medium under plane-wave illumination for several special cases, one of which is a medium free of particulate matter. It is easy enough to see the difference between clean and dirty air; it is another thing to say what the dirty atmosphere is carrying. The difficulties inherent in the transfer problem for more general cases are such that a considerable theoretical and experimental effort will be needed to resolve them. There are two distinct stumbling blocks. The first obstacle is a virtually complete lack of knowledge of the detailed scattering and absorption properties of typical aerosol particles; that is, nonspherical or irregular particles possibly coated with liquid or ice and having diverse chemical compositions. We have practically no information on how such particles scatter electromagnetic energy and how these properties change with scattering angle, with the wavelength and polarization of the incident energy, and with the complex refractive index of the particles with respect to the surrounding medium.

But these are just the properties we need to know to attack the problem; they are central to the transfer equations that must be solved. The second difficulty lies in the fact that we do not have efficient means of solving the relevant equations for media that contain particles. To invert the transfer equation for a turbid medium in order to ascertain the physical properties of the medium is an even more difficult problem. These two difficulties must be attacked and considerable progress made before we can say whether or not an inversion can be accomplished successfully. In a sense, our remote-sensing eyes are a bit blind in that we do not fully understand what we see.

RELEVANT PHYSICS

When a beam of electromagnetic energy is incident on particles, some of the energy is removed from the incident beam. The energy is removed by scattering and absorption. In general, the scattered energy has the same frequency or wavelength as the incident radiation, but other scattering processes can occur, such as Raman scattering or resonance fluorescence. The scattered radiation in these cases has a different frequency than the incident radiation, and the intensity of the scattered radiation is generally lower in magnitude than the intensity due to simple scattering; but the difference in frequency may offer an important advantage for remote sensing. The amount of energy removed from the beam by the particle or by inhomogeneity depends in a complicated way on the size and shape of the particle, on the refractive index of the particle relative to the surrounding medium, on the incident wavelength, and on the state of polarization of the incident wave.

If the initial intensity of the incident (unpolarized) beam is denoted by I_0 then after traveling distance dx along a path through the medium, the change in intensity will be

$$dI(x) = -I\beta(x)dx + E(x)dx$$

The quantity $\beta(x)$ denotes the volume extinction coefficient of the medium at point x, and E(x) denotes the radiation from sources at x. The volume extinction coefficient represents the net extinction due to scattering and absorption by the particles in the elementary volume element.

This simple one-dimensional equation can be integrated over the entire path OS, and the intensity at point S is

$$I(S) = I_0 \exp\left[-\int_0^S \beta(x')dx'\right] + \int_0^S E(x')\exp\left[-\int_{x'}^S \beta(x'')dx''\right]dx'$$

Defining the optical thickness in the medium by

$$\tau = \int_0^S \beta(x')dx' \text{ and } \tau' = \int_0^x \beta(x'')dx''$$

we have

$$I(S) = I_0 e^{-\tau} + \int_0^S E(x')e^{-(\tau - \tau')}dx'$$

The formal solution above serves to demonstrate that the intensity at S is composed of two distinct radiation fields: the incident field attenuated along the path OS by absorption and scattering processes, and contributions to the intensity due to emissions by the medium along the path, attenuated along the path x′S.

In general the source term consists of two parts: virtual emission, due to scattering of other radiation into the direction of interest, and true emission (for example, thermal emission). If we neglect the emission, or source, term, we have the usual form of the Lambert-Bouguer law. This relationship is in wide use to describe the attenuation of light by a scattering and absorbing medium. However it is deceptive since it tells us nothing about other radiation that is scattered into our beam. That information is contained in the source term E(x).

That part of the source term which is due to scattering is described in terms of a scalar phase function for the simple case when polarization is neglected. For the general case, where polarization is considered, the phase function becomes a phase matrix, and the intensity becomes a vector.

In principle, this scattering matrix contains all of the information available from a scattering experiment in an optically thin medium. The principal difficulty is the fact that in most cases we do not know the scattering matrix elements. Only for the special cases of homogeneous spheres, cylinders, and several other shapes do we have theoretical descriptions of the scattering matrix of the medium. For more complex particles we have practically no information.

Since atmospheric particles have a variety of shapes, sizes, and refractive indices, and in many cases can consist of an irregular nucleus with a liquid or ice coating which may or may not be homogeneous in composition or structure (Hidy, 1970; Amer. Chem. Soc., 1971; Bigg, Ono, and Thompson, 1970; Esmen and Corn, 1969; Abel, Winkler, and Junge, 1969; Lundgren and Cooper, 1967; Hänel, 1970; Pilat and Charlson, 1966; Charlson, Pueschel, and Ahlquist, 1969; MacKinnon, 1969; LeClare and Manganelli, 1971), the scattering properties of homogeneous spheres have limited application to this problem. Nevertheless, at the present time most investigators assume, as a first approximation, that particles behave as spheres. It should be noted that in some applications the assumption can lead to incorrect inferences.

Therefore, the scattering matrix elements of real aerosol particles should be studied. Such studies can be performed readily with current laboratory methods (Tůma and Gucker, 1969; Wyatt, 1968, 1969; Blau, McCleese, and Watson, 1970; Holland and Gagne, 1970). However, we wish to emphasize that there are many problems concerning the distribution of particulate pollutants that can be studied without a knowledge of the scattering phase matrix. Some of these problems will be discussed in the section entitled "Remote Methods of Measurement".

STATE OF THE ART OF RADIATIVE TRANSFER THEORIES

In this section, we shall discuss present day capabilities in dealing with problems of radiative transfer through an atmosphere that contains particles as well as the normal molecular constituents. It will be assumed that all the necessary input parameters are known. In particular, our capabilities to compute the following relevant quantities will be discussed: 1) emergent fluxes, 2) internal flux divergence, 3) intensity and polarization distribution, 4) heating rates (integration over wavelength), 5) inversion capability. This last item refers to our ability to invert the equation of radiative transfer appropriate to the model atmosphere in question in order to infer something as to the physical structure of the atmosphere, such as the particle-height distribution, distribution of an absorbing gas, etc. It is assumed that a given set of remotely sensed measurements such as the emergent intensity distribution as a function of wavelength, etc. are given. This desired capability is not to be confused with our ability to determine these distributions by means of a specially designed experiment, such as the use of a pulsed laser to determine height distributions of aerosols. We assume for the purposes of this discussion that the latter experiment can be performed. A summary of what we can and cannot do is in Table I.

When particles are present in an otherwise pure molecular

TABLE I

PRESENT DAY CAPABILITIES IN DEALING WITH PROBLEMS OF RADIATIVE TRANSFER THROUGH AN ATMOSPHERE THAT CONTAINS PARTICLES

Key:
Yes—The quantity can be computed.
No—The quantity can not be computed.

Model	Emergent Fluxes	Internal Flux Divergence	Intensity and Polarization Distribution	Heating Rates (integration)	Inversion
1. Plane-parallel, horizontally homogeneous atmosphere, with homogeneous boundaries					
a. Vertically homogeneous	Yes	Yes	Yes	Yes	No
b. Vertically inhomogeneous	Yes*	Yes*	Yes*	Yes*	No
2. Plane-parallel horizontally inhomogeneous atmosphere	No	No	No	No	No
3. Spherical atmosphere	Yes**	Yes**	Yes**	Yes**	No

*While this is soluble with currently available methods, it is felt that more work is needed on these solutions in order to make them more expedient.

**These problems are soluble in principle, but the solutions for them have not, at this time, been published.

atmosphere, the appropriate equation of radiative transfer becomes quite difficult to solve because of the complicated form of the scattering phase matrix attributed to the aerosols. Thus, to date, most of the computational schemes which have been developed to solve these problems involve "brute force" numerical integrations or random walk techniques (Herman and Browning, 1965; Herman, Browning, and Curran, 1971; Hansen, 1969; Collins and Wells, 1968; Thompson and Wells, 1971; Kattawar and Plass, 1968; Dave and Gazdag, 1970). The former methods, while capable of reasonably accurate solutions, require considerable computer time, while the latter suffer from lack of accuracy, or lack of detail in the angular distribution of the resultant intensities, again unless considerable computer time is used. Thus, while it is presently possible to compute the first four of the parameters listed above (as indicated by "yes" in Table I) for a plane-parallel, horizontally homogeneous atmosphere with homogeneous boundaries, with or without vertical inhomogeneities (that is, models 1a and 1b in Table I), considerable work on these problems is still required in order to develop more economical solutions. Our present capabilities do not permit an inversion of the relevant transfer equations for these two models, nor for any other of the models, as can be seen in Table I. If horizontal inhomogeneities are present in the atmosphere (model 2), then our present capabilities do not permit computation of any of the five listed parameters; and the same is true if there are horizontal inhomogeneities in the lower boundary (the earth's surface).

While the solutions to the above categories of problems are reasonably satisfactory for many practical applications, large deviations occur for low solar elevation angles, or for nearly horizontal observation angles, due to the spherical shape of the earth and atmosphere. The problems are further magnified when viewing is from a large height above the earth's surface, as from a satellite. Therefore, it would be desirable to develop solutions that take the spherical geometry into account. The same techniques that are used to solve the problems in categories 1(a) and 1(b) could, in principle, be used to solve problems with spherical geometry; however, at present, such solutions do not exist. Thus we can say that some simple but useful measurements can be made remotely, but the full potential will not be realized without some further basic work.

THE DEPOLARIZATION EFFECT OF PARTICLES ON ATMOSPHERIC RADIATION

Since the discovery by Arago in 1809 that the light from a blue sky is polarized, the effect of particles on skylight polarization has been observed and measured by large numbers of atmospheric physicists. All of these investigations have clearly indicated that the effects of particles on skylight polarization are large; hence, polarization offers a powerful means of monitoring the concentration and of studying different properties of particulate matter in the atmosphere. Extensive documentation of this point can be found in the classical treatise by Busch and Jensen (1910) and in papers by Jensen (1928) and in more recent comprehensive articles by Neuberger (1951, 1950) and Sekera (1951, 1956, 1957a, 1957b). As classical examples one can mention the observed decrease of the maximum degree of polarization from the average of 0.80 to 0.30 in the visible spectral region after the Krakatoa volcanic eruption, and the shift of the distance from the sun of the neutral point (point of zero polarization) from 17° to 34° after the Katmai volcanic eruption. Changes of similar magnitude have been measured in the Los Angeles area during typical smog conditions.

The physical reason for the large effects of suspended particles on atmospheric radiation is that the air molecules scatter the light according to the Rayleigh law, which is applicable to particles of sizes that are negligible with respect to the wavelength, while particles scatter according to a quite different and much more complicated law, depending on the shape and size of the particle. In the simple case of spheres, this law was derived by Mie in 1908 and has been used since as a first approximation to large-particle scattering. While in single Rayleigh scattering the light scattered in the direction 90° from the forward direction is completely polarized (that is, the intensity component parallel to the scattering plane has essentially zero magnitude), for most realistic models of Mie particle size distributions, the light scattered by particles in all directions is almost unpolarized (in the center of the visible region). Consequently, in a turbid atmosphere containing both air molecules and particles, the presence of particles can be noticed by a strong depolarization effect on the polarization of the clear Rayleigh atmosphere. Since the intensity of Rayleigh scattering varies as λ^{-4} while the intensity of particle scattering varies approximately as $\lambda^{-\beta}$ $(-2 \leq \beta \leq 2)$, the depolarization by particles is more pronounced for longer wavelengths. Moreover, since the molecular density is practically constant while the particle concentration is highly variable in time and space, the presence of aerosol particles can be recognized from rapid variations in the skylight polarization which increase in magnitude with increasing λ.

Although there is no basic difficulty in getting qualitative indications of the presence of particles in the atmosphere from skylight polarization measurements, making quantitative estimates of particle concentrations or other relevant parameters is much more difficult. First of all it should be remembered that *only after* the problem of multiple scattering in a Rayleigh atmosphere has been solved, can such an estimate be made. Attempts to obtain quantitative analyses of particles with the assumption of only primary Rayleigh scattering lead definitely to erroneous results, but extensive tables relating to scattering in a Rayleigh atmosphere are now available (Chandrasekhar and Elbert, 1954; Coulson, Dave, and Sekera, 1960). One complicating factor is the effect of ground reflection. If the ground reflects according to Lambert's law (that is, isotropic unpolarized reflection) depolarization effects proportional to the ground reflectivity result, while the positions of neutral points are unaffected by the ground reflection. If the ground reflection is specular, only a small depolarization can be noticed around 20° from the sun, but the positions of neutral points are significantly affected. The same effects appear in the skylight and in the upward emerging radiation from the atmosphere; however, the magnitudes of these effects are much greater for the latter, especially at the wavelengths of greater transparency in the atmosphere. Ground reflection effects can be eliminated either by using the different aspects of these effects, by monitoring different quantities, by statistical studies of measurements under particle-free conditions, or by introducing ground reflection into the radiative transfer theory by means of a reflection matrix the elements of which have been previously determined.

Another complicating factor is the multiple scattering in a turbid atmosphere that arises for large particle concentrations. In this case the quantitative analysis of the deviations of measured skylight polarization from the corresponding theoretical values for a pure Rayleigh atmosphere has to be based on the solution of radiative transfer in a turbid atmosphere.

REMOTE METHODS OF MEASUREMENT

Particulate measurement techniques fall into two distinct categories: remote and nonremote methods. Nonremote or direct methods have been described extensively in several reports (Nat. Air Pollution Cont. Admin., 1969; Podzimek, and Spurny, 1965; Mueller, et al., 1971; Lieberman and Schipma, 1969; Harris, 1971; Methods in Air Pollution and Industrial Hygiene Studies, Eleventh Conference, 1970; Lundgren, 1967; Charlson, Ahlquist, Selvidge, and MacCready, 1969; Steigerwalk, 1962). The remote methods involve the detection of atmospheric particulate matter by observing its effects on electromagnetic radiation and do not require obtaining actual samples. They may involve use of the sunphotometer (turbidity meter), laser radar, and surface, airborne, and satellite radiation instrumentation.

The indirect methods for measuring particulate matter are based on its effects on the electromagnetic spectrum. With certain necessary assumptions, measurements of the scattering and attenuation of radiation are used to obtain the total atmospheric particulate loading, the vertical aerosol distribution, and the distribution and dispersion of large concentrations of particulate material.

CURRENT EXPERIMENTS

The global turbidity network of the Environmental Protection Agency (EPA) uses a monochromatic radiation detector to measure the atmospheric turbidity, which is defined as the extinction coefficient for the vertical atmosphere due to aerosols. Ten years of data collected with the Volz sunphotometer, which measures the turbidity at 0.50 μm wavelength, have provided a climatology of turbidity over the U.S. These data have also been used to estimate particle loading and diffusivity in the lower layers of the atmosphere (Flowers, McCormick, and Kurfis, 1969; McCormick and Baulch, 1962; McCormick and Kurfis, 1966). At the present time the network is being supplied with a dual-wavelength instrument of greatly improved accuracy and precision. Extinction measurement at the two wavelengths of 0.50 μm and 0.38 μm will allow estimates to be made of the relative particle size distribution.

Searchlight beams were first applied to the study of the atmosphere by Waldram et al. (1952) and were later applied extensively by Rozenberg (1966) and his coworkers in Russia, and by Elterman (1969) in the United States. A comprehensive analysis of the searchlight method is available in Rozenberg's text (1966).

McLellan (1970) has shown that it is possible to relate the changes in the albedo of the earth over Los Angeles as measured from the geostationary spacecraft ATS-3 to the visibility and particle count in the local lower atmosphere over the city. This is perhaps the first quantitative detection of pollution from a satellite. Figure 5 shows that in this particular example the radiance decreases as the particle concentration increases, since the particles absorb light. The ordinate of the "Particulate matter" curve, K_m, is a measure of the solid-particle concentration near the ground; it is inversely related to the reflectance of a 1-cm^2 filter on which has been deposited the particulate matter in 1m^3 of air. The decrease of K_m and the simultaneous increase of the horizontal surface visibility indicate a decreasing particle concentration. Photographs taken in 1968 by astronauts also show pollution.

Laser radar is a relatively new technique for remotely sensing the properties of the atmosphere. Several recent summaries have been published which together provide a complete discussion of laser radar techniques (Derr and Little, 1970; Collis, 1969; Collis, 1970). In its simplest form, the laser radar (lidar) uses a laser to generate a short, high-power light pulse. As the pulse propagates through the at-

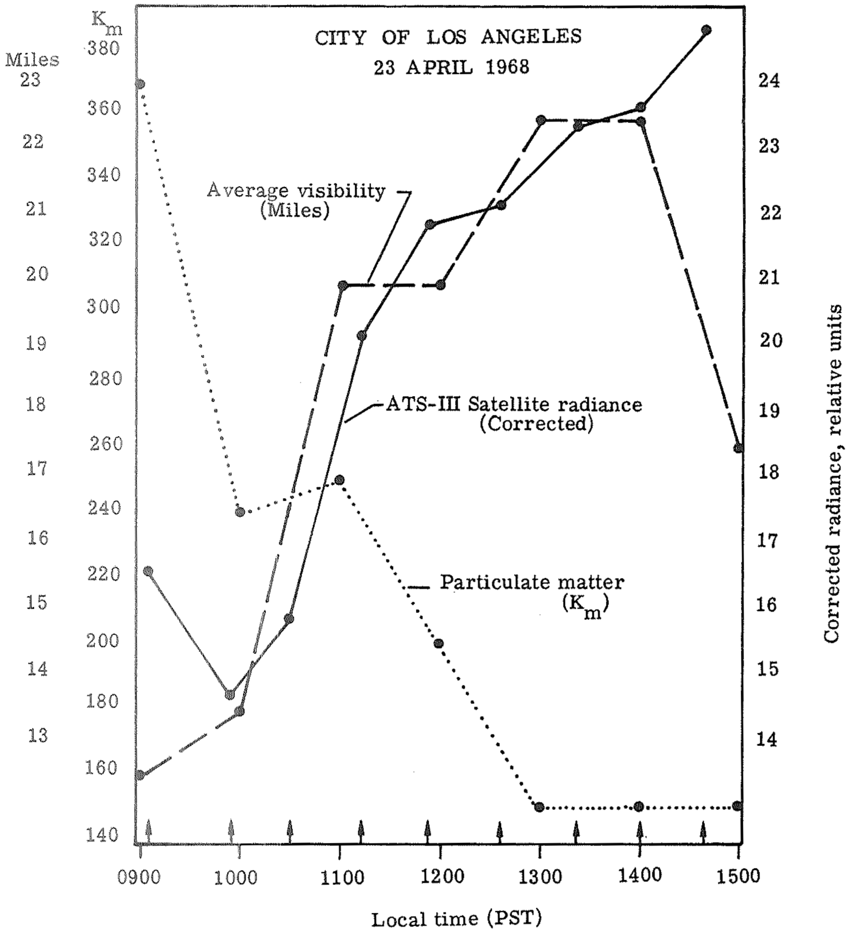

Figure 5.- Comparison of the changes in the earth albedo at Los Angeles, as measured from the geostationary spacecraft ATS-III, with the changes in the visibility and particle count in the local lower atmosphere. (From McLellan, 1970).

mosphere, backscattered light is collected by a telescope, collimated by suitable optics, filtered by narrow band interference filters to decrease the intensity of the background light from the sky, and measured with a photomultiplier. The signal from the photomultiplier can be fed into a suitable digital analyzer to provide a measurement of intensity of the light collectively backscattered by the atmospheric constituents as a function of range. The presence of particulate material can cause significant deviation from the echoes expected from a dust free atmosphere, and the presence of particles can thereby be detected. Laser radar systems in general are more complicated instruments than passive remote sensors; on the other hand, they provide the scattering properties of the atmosphere continuously as a function of range, typically with a spatial resolution of 100 meters, which greatly simplifies data interpretation. In addition, since the technique utilizes an extremely intense monochomatic source of known polarization, it is possible to discriminate very effectively against background sources. It should also be noted that, in contrast to passive techniques, further improvements in the intensity of the source can be expected as laser technology improves.

The first use of laser radar in the atmosphere was reported by Fiocco and Smullin in 1963. Since that time, a number of applications of the laser radar technique have been investigated. A number of investigators (Hamilton, 1966; Barrett and Dov, 1967; Johnson, 1969; Olsson et al., 1971) have demonstrated the ability of laser radar to measure the height of maximum mixing accurately and to monitor its temporal and spatial variation; measurements of this type can make a significant contribution to air pollution control and also to the verification of numerical models. Since laser radar can detect small changes in particle concentration, it is an excellent technique for observing the dispersal of particulate matter in stack plumes (Johnson, 1969) and also the dispersal of insecticides (Collis, 1968). The technique is directly applicable to research problems in atmospheric transport processes and also to operational problems.

Laser radar provides a very convenient and economical means of probing dust layers in both the stratosphere and mesosphere (Sandford, 1967; McCormick, Silverberg, Poultney, et al., 1967; Schuster, 1970; Grams, 1970; Lane, Ashwell, and Dagnall, 1971). For example, a ground based laser radar system has already been used to obtain information on the average characteristics and temporal variation of the vertical distribution of stratospheric aerosols over a two year period (Grams and Fiocco, 1967). In addition, studies of the meridional distribution of stratospheric aerosol particles have been performed recently with an NCAR airborne laser radar system. Airborne laser radar studies of the atmosphere have also been performed by the Langley Research Center of NASA and the Stanford Research Institute.

Other remote techniques proposed and under study are based on satellite-borne limb-scanning devices (Bullrich, 1967; MIT Aeronomy Program, 1971; Pepin, 1969; Pepin, 1970) observations of twilight (Volz, 1969; Bullrich, 1969; Volz, 1970), the small-angle scattering of sunlight (Bullrich, 1969; Newkirk and Eddy, 1964; Quenzel, 1970; Green, Deepak, and Lipofsky, 1971), and the degree of skylight polarization (Bullrich, 1969; Plass, 1956; Sekera, 1967). These techniques may be briefly described as follows:

The earth's limb can be scanned from a satellite using the sun or a star as a source. In this technique, extinction by the lower atmosphere is avoided. The variation in transmission and small angle scattering is measured as the sun sinks behind the horizon giving the vertical profile of the earth's atmospheric transmission along the line of sight in the stratosphere and mesosphere.

In the twilight experiment the vertical distribution of turbidity can be measured relatively easily by surface observations of the twilight sky radiation after sunset or before sunrise. As the sun's position changes the region of illumination changes vertically, permitting a vertical scan of the atmosphere using the scattered sunlight. Twilight measurements can also be made from a satellite.

The angular distribution of sunlight scattered by a few degrees in the aureole provides information for the determination of altitude and size distribution of aerosols using a spectrometer or filters. The wavelength variation of the scattering may be measured either from the surface or from balloons. The small angle scattering from particles compared to molecules is much greater than the large angle scattering.

The nature of the polarization of the radiation scattered by a gaseous atmosphere is known. By measurement of the polarization as a function of solar position and scattering angle the difference due to aerosols is determined and hence also the nature of the additional scatterers.

REMOTE MEASUREMENTS, CURRENTLY FEASIBLE

We have seen that it is possible to obtain remote measurements of particulate matter in different layers of the atmosphere. These measurements have limited geographical coverage and are only quasi-quantitative. We are not able to distinguish between man-made particles and those due to nature on the basis of the remotely probed signals alone. It does seem possible to determine the man-made contributions, however, from a knowledge of geographical distributions of the particles. Thus the real power of remote probing techniques lies in their ability to provide wide coverage at reasonable cost. The situation is similar to that experienced by meteorologists. The ordinary radiosonde is a simple, low cost, surprisingly accurate atmospheric probe; nevertheless, it took the satellite borne infrared sondes to make global observations of the state of the atmosphere realistically possible.

Albedo Measurements

The albedo of the earth represents the fraction of the sun's energy that is reflected back to space and never enters into the earth's thermodynamic system. The first generation of meteorological satellites has shown that the earth's albedo is only 29-30% compared to earlier estimates, which ranged from 35-40% (Vonder Haar and Suomi, 1971). In addition, the latitudinal distribution of albedo is found to be such that the equatorial regions absorb almost 40% more solar energy than was previously estimated. Furthermore, the first generation satellite observations of the outgoing longwave radiation showed the earth, considered as a whole, to be in radiative equilibrium with space, within the accuracy of measurement, on a time scale of months or seasons rather than years.

The earth's albedo is influenced by cloudiness, the gaseous molecules of the atmosphere, the dust it carries, and the underlying ocean areas and land surfaces. If we use 30% as the value of the earth's albedo, about 25% is due to clouds and the 5% remainder is due to the atmosphere and the earth's surface. Whereas the direct effect of particles on the global albedo is relatively small, their indirect effects on the global albedo can be greater. We know that particles can affect the droplet concentrations and size distribution in clouds, which in turn affect the optical transmission, reflection, and absorption properties of the clouds. We have not, however, established the magnitudes of these effects; particularly the contributions attributable to man's activities.

Because the net radiative input to a particular location on the earth is the difference between two large numbers, that is, the solar input and the long-wave loss, a small change in albedo can result in a large change in net heat input to the area. Simple models of climate such as those described by Sellers (1969) and Budyko (1969) predict new ice ages if the solar constant (or albedo) changes by only 2-4%. The possibility that these dramatic effects on climate could result from changes in albedo of plausible magnitude point to the need for continuous monitoring of the earth's albedo. The accuracy requirements as estimated by various groups range from 0.1 to 1%.

Ideally one would want to measure the flux of radiation at a level just above most of the atmosphere. However, to obtain reasonably long satellite lifetimes it is necessary to operate at 500 km or higher. The radiation streaming through a unit horizontal surface at this altitude originates from different locations on earth; nevertheless, the total flux that passes through the surface generated by the satellite motion is equal to the total flux leaving the earth (if we assume that the orbit is approximately polar). The horizontal variations at the satellite level will be less than at a lower level but the totals will be identical. Albedo determinations made from scanning radiometers carried on earth-oriented spacecraft obtain their albedo values by using a model that determines flux of upwelling radiation from measurements with a radiometer that has a narrow field of view. Such albedo determinations are very useful for many purposes, but it is not likely that one can obtain the high accuracy needed by using this technique because cloud directional reflectivity departs so strongly from that given by the simple cosine law. Moreover, cloud reflectivity depends on thickness, texture, drop size distribution, layering, albedo of the underlying surface, and possibly other things as well. Because of these limitations, we recommend that direct flux measurements be made by using a flat plate radiometer positioned parallel to the earth's surface.

Albedo Measurements—The Sampling Problem

Even if we had a perfect instrument on an earth oriented spacecraft that held the radiometer parallel to the earth's surface, we could not obtain the desired accuracy because there is no satellite orbit that overflies all parts of the earth at all local times, all equally. Polar orbits oversample the polar regions and undersample the equatorial regions. Worse yet, a true polar orbit has virtually the same local time during its northward motions and a 12 hour different but uniform local time on the other half of the orbit. Moreover this local time changes slowly, passing through 24 hours in one year. It is well known that cloudiness (and thus albedo) shows a strong diurnal variation, especially over the continents.

We use a polar orbit as an example of how bad the sampling problem can get. Most meteorological satellites have been launched into sun-synchronous orbits where the orbit plane tends to remain fixed relative to the sun. If the spacecraft altitude and orbit inclination are trimmed fine enough the orbit precession can be controlled so that its period is just one year. When the trim cannot be adjusted a slow drift changes the local time of satellite overflight. Albedo measurements from such a space platform will again stretch the diurnal change in cloudiness over a long period so that trends of the real albedo change could be hidden in the change in local sampling time. If one chooses a geo-stationary orbit an area in the field of view is under continuous surveillance and one has the full 24-hour view, but from only one angle. Thus we see that no single space platform can meet all sampling requirements but several in different orbits can meet these requirements more satisfactorily. House (1962) has shown that two spacecraft at different altitudes and inclinations having omnidirectional detectors meet the sampling criteria within a few percent. Presumably additional spacecraft with earth pointing capability could do much better. We recommend that studies to determine the optimum configuration of the spacecraft fleet be carried out, and that it be determined whether spacecraft being developed in existing programs could be utilized to meet this need. We wish to emphasize that it is not possible to obtain high precision albedo observations from only one spacecraft no matter how good the instrument it carries might be.

Albedo Measurements—Instrumental Problem

According to the recommendations made by SMIC (1971) the satellite system must be capable of "monitoring the temporal and geographical distribution of the earth-atmosphere albedo and the outgoing flux (IR) over the entire globe with an accuracy of at least 1%."

Geographical distribution of the upwelling solar and infrared radiation fluxes is presumably obtainable, especially if the problems of sampling are solved as was suggested previously, but detection of long period temporal changes in these fluxes demands extreme instrument stability. Albedo is a ratio, thus if one could use the same instrument to measure the solar input and the solar radiation reflected from the earth separately one might obtain the ratio more accurately.

Practical instruments do have errors. In a space environment we are not assured that the instrument constants will not change with time. The absorptivity may change due to aging; the cosine response and the calibration constants may change as well. Many of these uncertainties can be removed if the instrument can be calibrated right on the space platform. It is important that long time measurement capability be assured and that inter-comparisons between the different instruments on the different satellites be a firm requirement of the system used.

We have just described in some detail key requirements for the measurement of the geographical and temporal distribution of albedo. The requirements for accuracy in the measurement of infrared flux leaving the earth are very similar. In addition, it is necessary to have high accuracy in the measurement of the solar constant, certainly better than 0.5%. Thus we endorse the recommendations on this subject made in SMIC and strongly urge that they be carried out in the immediate future. We do not anticipate any unusual difficulty in meeting these requirements.

Measurements of Stratospheric Particle Distributions

Stratospheric particle distributions are well suited for remote study from satellites because measurements can be made through the earth's limb. With this geometry, radiation scattered or emitted by the particles can be measured relatively free of interference from radiation emanating from denser lower layers of the atmosphere of the earth's surface. In addition, vertical distributions can be determined by scanning the instrument field of view from the top of the atmosphere to the top of whatever cloud layer is present.

The presence of particles in the stratosphere can be sensed in several ways. The sun can be used as a source of radiation for an extinction experiment at several wavelengths in the visible or near ultraviolet to provide information on concentrations and size distributions. Alternatively, thermal radiation emitted and scattered by the particles can be measured. We shall consider prospects for experiments based on both types of measurements.

An extinction experiment designated Wyoming SAM, designed to provide information on stratospheric aerosol distributions, is planned for OSO-J, which is scheduled for launch in the fall of 1974 (Pepin, 1969; Pepin, 1970). This experiment, which takes advantage of the orbit and very precise stabilization of the OSO satellite, will measure the attenuation of the solar radiation passing over the earth's limb in three wavelength bands near 370 nm, 450 nm, and 1 μm. The satellite motion will provide a scan through the limb giving vertical resolution of about 0.5 km in a zone about 60° wide centered at the equator. Pepin, the principal investigator, believes that by making measurements at these three wavelengths, it will be possible to separate the effects of the Rayleigh atmosphere and the particles and then to determine particle concentrations for the most appropriate of several assumed size distributions with an accuracy estimated to be 1 to 2 per cent.

The OSO experiment is an excellent example of utilizing an existing satellite for a pollution-oriented study. We believe, however, that the payoff from the OSO experiment could be increased even more by changing the satellite orbit to include coverage to latitudes up to about 60°. Our reasoning is as follows: The selective chopper radiometer now aboard the Nimbus spacecraft provides accurate stratospheric vertical temperature profiles to an altitude of about 45 km. Using this information it should be possible to model stratospheric circulations at latitudes north of 30°. The validity of the models can then be checked using the data on particle distributions measured from the OSO experiment. In effect the dust distributions will serve as tracers of the exchange processes between stratosphere and troposphere believed to occur in the zone between the tropical and polar tropopause discontinuity. An additional important reason for extending the geographical coverage of the OSO experiment is to obtain data for both modeling and monitoring purposes on particle distributions in regions where SST operations will be concentrated.

Stratospheric aerosol distributions also can be determined by examining the light back-scattered from the nadir. The Back-Scatter Ultraviolet (BUV) experiment on Nimbus 4 satellite measures the solar energy scattered from the nadir in the spectral band 250-380 nm. Solar energy at wavelengths less than 285 nm does not penetrate to the ground and is scattered by just the atmosphere. Energy within the band 250-275 nm does not even reach the troposphere and is scattered just by the stratosphere. Because the albedo for single scattering is very small, multiple scattering is unimportant and the complications due to its contribution may be neglected. The measured radiances can be inverted by standard techniques to yield the scattering coefficient as a function of height. The difference between the derived coefficient and the scattering coefficient for the gaseous atmosphere thus gives the large-particle scattering coefficient. Assumptions about the scattering characteristics of the large particles have to be made then in order to relate this coefficient to the vertical profile of the large-particle concentration.

Polarization Measurements to Determine Atmospheric Turbidity

The measurement of the polarization of the radiation emerging from the atmosphere can be performed by a photopolarimeter that should be designed to measure at least three Stokes parameters if the measurement is restricted to linear polarization. This restriction is fully justified since the ellipticity (defined by the 4th Stokes parameter) of the radiation from a sunlit atmosphere is usually very small.

The most efficient system for measuring these three parameters (I, Q, U) consists of three channels, one containing an analyzer with the transmission plane in, say, the vertical direction. a second containing an analyzer with the transmission plane 45° from the vertical direction, and the third channel containing only a neutral filter that reduces the measured intensity to half (in order to achieve the same dynamic range as with the other two channels). From the radiation intensities as measured from these three channels (Haraharan, 1969) one obtains the Stokes parameters I,Q,U in relative units, the degree of polarization, and the deviation of the plane of polarization from the vertical direction.

It should be mentioned that any instrument that measures the intensity of radiation can be easily adapted to polarization measurements if two polarizing filters with transmission planes oriented as mentioned above are periodically inserted in the optical path. When a very fast response of the polarimeter is not required, the three channels can be replaced by only one with a rotating analyzer before a photodetector.

Such an instrument can be easily adapted for the measurement of the positions of neutral points.

From several years experience in ground-based and airborne polarization measurements, theoretical investigations of the skylight, and studies of the radiative transfer in general conducted at the University of California at Los Angeles, the following applications of polarimetry in connection with remote sensing of air pollution may be proposed:

1. It is possible to monitor low level industrial and other man-made particle pollution by measuring skylight polarization in a rather dense network of observing stations, each equipped with a fully automatic photopolarimeter and using a helicopter-borne polarimeter periodically to assess the effect of ground reflection. Measurement of the intensity gradient in the sun's aureole together with measurement of the shift of neutral points provides an estimate of the size distribution and concentration of particles at the ground and their variation with height in the layers below the inversion.

2. For monitoring man-made particle pollution and natural particulate matter in inaccessible regions, polarimetry from a satellite can be used. The intensity and polarization of radiation emerging from a target area should be measured continuously from the satellite during its traverse over the area to secure data equivalent to a scan through varying directions of the line of sight. Since in this case the ground reflection plays a very important role, cloudiness and local variation of albedo should be checked by normal imaging of the area. The satellite traversals should be as close to zenith as possible in order to minimize the effect of stratospheric pollution.

3. For monitoring the overall global turbidity (and pollution), stations at regions (such as the arctic or antarctic) far from sources of air pollution should be equipped with fully automatic photopolarimeters. The atmospheric turbidity at such locations can be expected to be small; hence, the polarimetric method is probably the method of choice for accurate and reliable measure-

ments of turbidity, since the usual measurements of atmospheric transmission will fail unless extreme care is taken in standardization.

4. Stratospheric turbidity can be measured by polarimetry from a geostationary satellite (ATS-type). The scanning photometer can be modified for this purpose by periodically inserting polarization filters as mentioned above. By measuring the intensity gradient across the terminator and corresponding values of the polarization against the dark background of the earth's surface and lower troposphere, the aerosol component can be determined.

All polarization measurements should be performed in several narrow spectral bands covering the near ultraviolet and visible regions. Because the ratio of the strengths of the molecular and aerosol components varies considerably throughout this region, a very useful check on the consistency of the measurements is gained by this arrangement.

REMOTE SENSING: SOME DIRECTIONS FOR FUTURE EXPERIMENTS

A natural extension of the laser radar techniques that have already been demonstrated with ground-based and airborne systems would be a satellite experiment to obtain measurements of the spatial distribution of particles in the stratosphere on a global basis. Figure 6, due to G. Grams, shows relative laser radar echo intensities as a function of altitude for a system operating at a wavelength of 500 nm. The figure shows, for example, that a ground-based system capable of probing up to about 35 km at the specified wavelength is also capable of observing backscattered signals from the surface to about 15 km from a satellite altitude of 200 km (note that the signal intensities in those altitude regions for curve (c) equal or exceed the signal intensity at about 35 km on curve (a)). We also point out, with reference to Figure 5, that for the ground-based system the signal varies by over seven orders of magnitude from the surface to the stratopause, whereas for satellite experiments, the required dynamic range of the detector is less than three orders of magnitude. This difference, coupled with lower

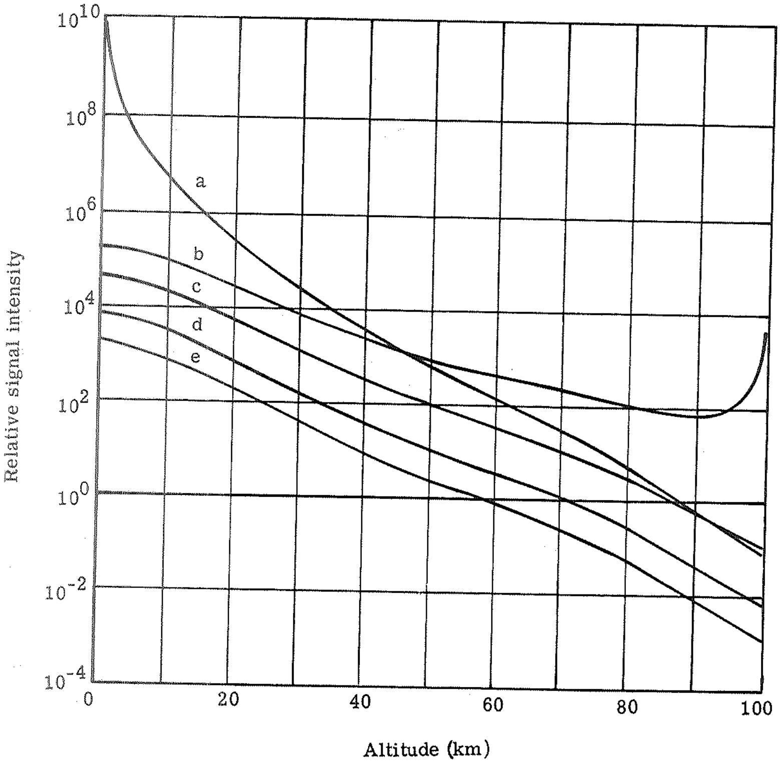

Figure 6. - Relative intensity of laser radar echoes for (a) ground based laser radars and for downward-looking laser radars at (b) 100 km, (c) 200 km, (d) 500 km, and (e) 1000 km.

(From Grams, 1970)

atmospheric attenuation losses for the satellite platform, demonstrates that such a system would have distinct advantages over present ground-based systems. In addition, the active system allows one to select the atmospheric path to be observed as well as the horizontal and vertical resolution of the measurement. It is within the state of the art to obtain vertical (and horizontal) resolutions of the order of 100 m from orbiting satellites. With a satellite-borne laser radar, long term monitoring of tropospheric and stratospheric dust would be possible and could be used to establish the effects of both natural phenomena and man's activities on the total amount of aerosol particles and their spatial distribution in the atmosphere. Further, the exploitation of laser radar measurements of scattered radiation using polarization, multiple-angle, and multiple-wavelength techniques to obtain additional information about the distribution of particle sizes is under development (Haraharan, 1969; Palmer, 1970; Reagan and Herman, 1970; Reagan and Webster, 1970).

Many of the difficulties in achieving desired geographical coverage associated with experiments involving observation of sunlight through the limb can be avoided by measuring thermal infrared radiation emitted and scattered by the particles, again viewing through the limb but now against the deep-space background. In this case orbit requirements are less stringent and global coverage can be achieved with a single satellite.

The radiation from the particles is made up of a directly emitted component and a component originally emitted by the earth or in the troposphere and then scattered by the particle cloud. The spectral region of importance is determined by the temperature of the earth and extends from about 4 to 40 μm. The aerosol particles are thus relatively small with respect to wavelength (see the section entitled "Interactions") and information on both concentrations and size distributions can be obtained if measurements are made at several well-separated wave-lengths.

If measurements are made by means of a spectrometer with a spectral resolution of about 5 cm^{-1} rather than a radiometer at a few fixed wavelengths, then it may be possible to obtain information on the chemical nature of the particles.

The spectral region from about 4 to 40 μm, is often referred to as the fingerprint region since it contains absorption bands characteristic of the chemical groups of which the gases or particles are composed. The changes in index of refraction and absorption coefficient responsible for these absorption bands will also affect the scattering and emission coefficients in a characteristic manner. Information on chemical structure can be obtained from the thermal infrared emission-scattering spectrum provided there is not too much interference from emission bands due to infrared-active gases in the stratosphere. Such interference is probably not excessive for many of the chemical groups of importance. Nevertheless this technique is very difficult and requires much further study. Conrath, et al. (1970), using the IRIS spectrometer with 5 cm^{-1} resolution were unable even to detect trace gases in the atmosphere when looking straight down from the Nimbus spacecraft because of overlap and interference from H_2O and CO_2 bands.

Other spectroscopic techniques such as those referred to in the section on gaseous pollutants could also be used to study dilute particle layers. These refined systems require much greater technological sophistication than is on the systems currently being flown on spacecraft.

The thermal infrared experiment is obviously a difficult one. However, it can provide more information on dilute aerosol dispersions than any other technique and should be carefully considered, particularly for the shuttle where the weight penalty will not be too severe. The feasibility of a multi-purpose instrument serving for study of particulate and gaseous pollutants and for infrared astronomy should also be studied.

RECOMMENDATIONS

A Coordinated Research Program

1. We recommend initiation of a coordinated physio-optical research program whose purpose will be to advance our level of understanding of the optical properties and behavior of the real atmosphere. We feel strongly that the most effective way to achieve this purpose is to identify a center devoted to that purpose. If none can be identified, such a center should be organized.

Earth's Radiation Budget

2. *Global Albedo.* We recommend immediate attention to the task of measuring the earth's albedo and its long-term variability. We advise the use of flux sensors detecting the ratio of outgoing to incoming solar radiation simultaneously on satellites in different orbits. An accuracy of 1 percent or better is required.

Investigation is required of:

(a) The instrumental problems, including initial standardization and intercomparison in orbit.

(b) The sampling problem—what groupings of available orbital types give suitable earth coverage?

(c) The organizational problem presented by a single experimental project of long duration requiring space on several different types of satellites.

(d) The possibilities of international cooperation.

Terrestrial Radiation

3. We recommend monitoring of the outgoing flux of terrestrial radiation with the same global coverage and long-term stability as the albedo measurement.

Monitoring Atmospheric Particles
Satellite-Borne Methods

4. We recommend that consideration be given to broadening the geographical coverage of an experiment like that planned for the OSO-J stratospheric particle experiment to include measurements of distributions at higher latitudes. This will provide, quickly and economically, basic data for evaluating the stratospheric aerosol problem.

5. We recommend study of the use of a photopolarimeter in a geostationary satellite. We also recommend use of a cooled infrared spectrometer from a near-earth orbit for

study of more dilute distributions than can be sensed with photometers and to furnish information on the chemistry of the particles.

6. We recommend monitoring the atmospheric turbidity on a global scale by measuring the polarization of upwelling radiation with fast-response photopolarimeters, from particular target areas, keeping the area in the field of view during a satellite traverse in order to obtain information for a range of angles.

7. We recommend determination of stratospheric turbidity by studying the intensity and polarization gradients across the terminator as measured from satellites by existing photometers, modified to measure the polarization.

8. We recommend development of satellite-based lasers for monitoring the spatial distribution of stratospheric and tropospheric aerosols on a global basis.

Monitoring Atmospheric Particles—Ground-Based Methods

9. We recommend that a world-wide network of atmospheric turbidity monitoring sites be established in order to determine what changes, if any, in world-wide turbidity are occurring, or will occur in the future, due to man-made particulate matter. More specifically,we recommend monitoring by laser radar of the particle content of the lower stratosphere by both ground-based and airborne systems.

10. For determining low-level turbidity near pollution sources we recommend a net of observing stations equipped with:
(i) Fully automatic photopolarimeters to measure the degree of polarization of the skylight and the positions of the neutral points.
(ii) Instruments to measure the diffuse intensity gradient in the solar aureole.

11. For determining the secular trends in atmospheric turbidity, we recommend ground-based skylight polarization measurements in locations of low turbidity (mountain tops, arctic and/or antarctic regions).

Supporting Studies

12. We recommend study of how the scattering matrix elements of real aerosol particles differ from those of spherical particles; and how they change with wavelength, particle size, refractive index, size distribution, and shape. These measurements can be made with randomly oriented particles, using polar nephelometers.

13. Concurrent efforts should be applied to developing mathematical models of the scattering properties of nonspherical randomly oriented particles. Such models should be tested against the measured properties and improved. We must also develop improved models of the transfer of electromagnetic energy in the real atmosphere, including the following:

(i) Develop more refined computational models for the plane-parallel, horizontally homogeneous atmospheres (models 1(a) and 1(b) in Table I) in order to provide more accurate results requiring less computational time. Also, results from existing techniques should be cross-checked against one another to provide some insight into their relative accuracy.

(ii) Research should be inaugurated to incorporate spherical geometry into these models, either by modifying existing models or through developing new techniques.

(iii) Research should be inaugurated to develop models capable of handling horizontal inhomogeneities.

(iv) Current models should be employed to infer the consequences of increasing levels of atmospheric turdibity, using known or suspected chemical compositions of man-made and natural aerosols.

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APPENDIX

AFFILIATIONS AND ADDRESSES OF THE PARTICIPANTS

Mr. John C. Arvenson
National Aeronautics and
Space Administration
Ames Research Center
Moffett Field, CA 94035

Mr. Wendell G. Ayers
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 156
Hampton, VA 23365

Dr. Anthony R. Barringer
Barringer Research, Inc.
c/o Environmental Measurements, Inc.
215 Leidesdorff
San Francisco, CA 94111

Dr. Jacob Becher
Old Dominion University
Norfolk, VA 23508

Dr. Henry H. Blau, Jr.
A. D. Little, Inc.
Acorn Park
Cambridge, MA 02139

Dr. David E. Bowker
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 214-A
Hampton, VA 23365

Dr. Charles E. Byvik
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 187
Hampton, VA 23365

Dr. George L. Clarke
Biology Department
Woods Hole Oceanographic
Institution
Woods Hole, MA 02543

Dr. David E. Delzell
Old Dominion University
Norfolk, VA 23508

Dr. Seibert Q. Duntley
Director, Visibility
Laboratory
University of California/
San Diego
Building 348
La Jolla, CA 92037

Dr. Gifford C. Ewing
Woods Hole Oceanographic
Institution
Woods Hole, MA 02543

Dr. C. B. Farmer
Space Sciences Division
183B Room 353
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103

Dr. Robert S. Fraser
Laboratory for Meteorology and Earth Sciences
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Dr. John C. Gille
Department of Meteorology
Florida State University
Tallahassee, FL 32306

Dr. Gerald W. Grams
National Center for Atmospheric Research
P. O. Box 1470
Boulder, CO 80301

Mr. Thomas Haig
Space Science and Engineering Center
University of Wisconsin
1225 West Dayton Street
Madison, WI 53706

Dr. Philip L. Hanst
Division of Chemistry and Physics
APCO Technical Center
P. O. Box 12055
Research Triangle Park, NC 27709

Dr. Franklin S. Harris, Jr.
Old Dominion University
Norfolk, VA 23508

Dr. Benjamin M. Herman
Institute of Atmospheric Science
University of Arizona
Tucson, AZ 85721

Mr. Alfred C. Holland
National Aeronautics and Space Administration
Wallops Station
Wallops Island, VA 23337

Dr. Samuel Katzoff
National Aeronautics and Space Administration
Langley Research Center
Mail Stop 102-A
Hampton, VA 23365

Dr. William W. Kellogg
Associate Director
National Center for Atmospheric Research
P. O. Box 1470
Boulder, CO 80301

Dr. J. D. Lawrence, Jr.
Mail Stop 401
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23365

Dr. A. Lefohn
Division of Chemistry and Physics
Environmental Protection Agency
P. O. Box 12055
Research Triangle Park, NC 27709

Mr. Jules Lehmann
Code SRF
National Aeronautics and
Space Administration
Washington, DC 20546

Dr. Claus B. Ludwig
General Dynamics
Corporation
P. O. Box 1128
San Diego, CA 92112

Dr. John Ludwig
Office of Air Programs
Environmental Protection
Agency
5600 Fishers Lane
Rockville, MD 20852

Dr. Gene G. Mannella
Director of Technology
DOT Transportation Systems Center
55 Broadway
Cambridge, MA 02142

Professor William H.
Matthews
MIT Office 26-169
Massachusetts Institute of
Technology
Cambridge, MA 02139

Dr. S. H. Melfi
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 401-A
Hampton, VA 23365

Mr. Gary North
Remote Sensing Specialist
EROS Program
Room B-206
NASA/Mississippi Test
Facility
Bay St. Louis, MS 39520

Dr. George S. Ofelt
Old Dominion University
Norfolk, VA 23508

Mr. Donald H. Pack
Deputy Director, Air Resources Laboratories
National Oceanic and Atmospheric Administration
8060 13th Street
Silver Spring, MD 20910

Dr. Arch B. Park
Code SRR
National Aeronautics and
Space Administration
Washington, DC 20546

Dr. Theodore Pepin
University of Wyoming
Laramie, WY 82070

Dr. Henry G. Reichle, Jr.
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 401-A
Hampton, VA 23365

Dr. G. D. Robinson
Center for Environment
and Man, Inc.
(University of Connecticut)
275 Windsor Street
Hartford, CT 06120

Dr. James M. Russell, III
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 494
Hampton, VA 23365

Mr. Alexander Sadowski
National Oceanic and Atmospheric Administration
Room 1021
6010 Executive Boulevard
Rockville, MD 20852

Professor Zdenek Sekera
Institute of Geophysics and
Planetary Physics
U.C.L.A. Space Science
Center
Los Angeles, CA 90024

Mr. John W. Sherman III
Manager, Spacecraft
Oceanography Project
Naval Oceanographic
Office
Naval Research Laboratory
Washington, DC 20390

Dr. Verner Suomi
Director, Space Science and
Engineering Center
University of Wisconsin
1225 W. Dayton Street
Madison, WI 53706

Dr. Morris Tepper
Code SRD
National Aeronautics and
Space Administration
Washington, DC 20546

Mr. Peter White
TRW Systems, Inc.
One Space Park
Redondo Beach, CA 90278

Mr. William G. Witte, Jr.
National Aeronautics and
Space Administration
Langley Research Center
Mail Stop 214-A
Hampton, VA 23365

Mr. Harold W. Yates
Director, Satellite Experiment Laboratory
National Environmental
Satellite Service
National Oceanic and Atmospheric Administration
FOB #4, Room 0135
Suitland, MD 00233

Dr. John M. Zeigler
V.I.M.S.
Gloucester Point,
VA 23062

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