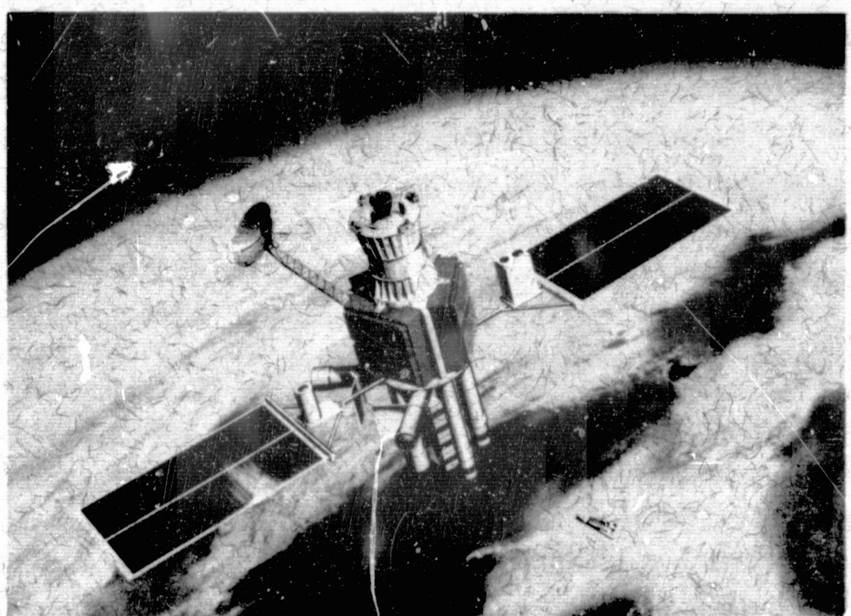
JPL PUBLICATION 78-54

(NASA-CR-157558) UPPER ATMOSPHERE RESEARCH SATELLITE PROGRAM Final Report (Jet Propulsion Lab.) 62 p HC A04/MF A01 CSCL 04A G3/46 N78-30750 Unclas 29115

Upper Atmosphere Research Satellite Program

Final Report of the Science Working Group



July 15, 1978

National Aeronautics and Space Administration

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract No. NAS7-100.

Preface

The work described in this report was performed by the Upper Atmosphere Research Satellite (UARS) Science Working Group under the cognizance of the UARS Development Preproject of the Office of Technology and Space Program Development of the Jet Propulsion Laboratory.

UPPER ATMOSPHERE RESEARCH SATELLITE

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Abstract

A Science Working Group was established in October 1977 by the Solar-Terrestrial Office of the Office of Space Sciences, NASA, to develop a satellite program to conduct research on the chemistry, energetics, and dynamics of the upper atmosphere. This publication is the final report of that Group, and outlines the scientific goals of the Upper Atmospheric Research Program, the Program requirements, and the approach toward meeting those requirements. An initial series of two overlapping spacecraft missions is described. Both spacecraft are launched and recovered by the STS, one in the winter of 1983 at a 56-deg inclination, and the other a year later at a 70-deg inclination. The duration of each mission is 18 months, and each carries instruments to make global measurements of the temperature, winds, composition, irradiation, and radiance in the stratosphere, mesosphere, and lower thermosphere between the tropopause and 120-km altitude. The program requires a dedicated ground-based data system and a science team organization that leads to a strong interaction between the experiments and theory. The Program is a natural evolution from the present planned series of atmosphere research satellites, and includes supportive observations from other platforms such as rockets, balloons, and the Spacelab.

Part I. Satellite Program

I. Introduction

There has been increasing concern in recent years about the sensitivity of the Earth's atmosphere to external influences associated with natural phenomena and changes arising from by-products of various human activities. Long standing curiosity about atmospheric evolution and the factors influencing climate and weather has been sharpened and refocused by the discovery of technological threats that introduce the possibility of inadvertent atmospheric modification. Such changes, occurring both in the troposphere and the upper atmosphere, have far-reaching consequences for the terrestrial habitat, and may eventually set the basic constraints governing man's life on this planet. These potential threats, and other possible changes that may occur in the atmosphere, highlight the need for a long-term program of scientific research directed toward improving knowledge of the physical and chemical processes occurring in the earth's atmosphere.

The Upper Atmosphere Research Satellite Program (UARSP) is an important new program aimed at improving our knowledge of the atmosphere above the troposphere, including those regions that are known to be especially susceptible to substantial change by external agents. UARSP will provide a focus for the resolution of scientific questions relating to the chemistry, dynamics, and overall energy balance of these regions, particularly with regard to the stratosphere, mesosphere, and lower thermosphere. Through a balance between measurements, theoretical studies of basic processes, and model analysis, it seems likely that substantial progress can be made in solving the outstanding physical and chemical problems of these regions. The need for extensive theoretical activity coupled to data and model analysis is a recurrent theme of the program and one which the Science Definition Group (SDG) firmly endorses.

The principle measurement goals of UARSP include long-term observation of solar irradiation at ultraviolet wavelengths, the global distribution and time variations of atmospheric trace species, and the dynamic behavior of the upper atmosphere. Knowledge of the solar flux and its variations is of basic importance to problems of atmospheric composition and structure. Likewise, global observations of atmospheric trace constituents relate directly to questions of upper atmospheric modification. Closely related to the question of composition is the extent of vertical and horizontal transport. The projected determination of winds in the upper atmosphere on a global scale opens the way to the study of a number of important scientific questions using a combination of theory and observation.

At high magnetic latitudes, influences associated with solar and magnetospheric energetic protons and electrons, together with ionospheric electric fields, act upon different parts of the upper atmosphere. High-energy protons from solar flares, for example, penetrate the stratosphere creating reaction products that remove ozone. Similarly, energetic electrons from the magnetosphere influence chemical processes in the mesosphere. Through a variety of instruments and missions, UARSP will be able to examine these events in the light of dynamic models of atmospheric response.

A major challenge addressed by the UARSP Science Working Group (SWG) has been the need to devise a framework for an evolutionary program centered on spacecraft observations extending over a period of five to ten years. The approach taken by the SWG has been to identify what it believes to be the key scientific questions that must be answered to understand the fundamental character of the upper atmosphere. With these scientific goals in mind, the first two satellite missions of a long-term research program have been identified; these missions meet additional constraints related to instrument and spacecraft technology.

In assigning priorities to investigations and structuring these missions, account has been taken of the fact that other programs and measurement platforms will be needed to answer some of the key scientific questions. The Measurement Strategy document of the NASA Upper Atmospheric Research Program points out that the data concerning some questions can be gathered most effectively by balloons and aircraft. Similarly, the SWG took into account the relative roles that UARS and the Space Shuttle will play. These two platforms have different but complementary capabilities. The Shuttle can carry large, heavy, complex, high-bit-rate experiments for short missions (7 to 30 days). Using the planned Spectroscopy and Lidar Facilities, the Shuttle is capable of short, intensive investigations. During these flights, it will be possible to use large, sensitive instruments to detect species having very low concentrations. In addition, the Shuttle will be well suited for study of processes requiring only limited observing periods (e.g., diurnal variations) and the testing of new measurement concepts. In developing an overall strategy for its Upper Atmospheric Research Program, the contributions and advantages offered by UARSP must be balanced with information derived from other programs such as AMPS, Spacelab + Power Module, OPEN, and other future activities.

From extensive studies by the Jet Propulsion Laboratory and the Goddard Space Flight Center, it appears that the UARSP experiments can be accommodated by a satellite possessing moderate size, weight, power, and data-rate capabilities. The scientific objectives of the two candidate missions identified in this report require global observations of about 18 months duration, with launch of the two spacecraft separated by 12 months and timed so that overlapping measurements during two northern-hemisphere winters can be obtained. With such satellites and the recommended instrument complement, investigations of mean chemical distributions and budgets, radiative balances, atmospheric dynamics, interactive couplings, and other processes can be initiated.

It is anticipated that the UARS Program will be a major contribution by the United States to the international Middle Atmosphere Program (MAP), planned to reach a maximum of scientific activity in the mid-1980s. To a large extent, the scientific objectives of UARSP and MAP are the same, and it can be expected that considerable coordination between the programs will develop, especially with regard to joint ground, balloon, and satellite observations.

II. Programmatic Background

The idea that man-made pollutants can adversely affect the upper atmosphere came to public attention in 1971 when it was suggested that exhaust emissions from high-altitude, supersonic aircraft could alter the concentration of stratospheric ozone. As a result, the Federal Government established a three-year study, the Climatic Impact Assessment Program (CIAP), under sponsorship of the Department of Transportation (DOT) to study possible physical, biological, social, and economic effects that might result from aircraft operations in the stratosphere. In 1972, the National Academies of Science and Engineering established the Climatic Impact Committee (CIC) to advise DOT and CIAP. In 1975, CIC issued a report that expressed serious concern about the possible reduction of stratospheric ozone from increased NO_x emissions in the upper atmosphere. In addition, CIC also suggested a potential impact on the stratosphere of Space Shuttle exhaust effluents emitted into the atmosphere.

In 1974, it was postulated that relatively inert chlorofluoromethanes released at the Earth's surface accumulate in the atmosphere and are slowly transported into the stratosphere, where they are photodissociated by UV radiation. The chlorine thus released subsequently reacts catalytically with ozone, causing the destruction of ozone.

In response to these growing concerns, a Federal Task Force on the Inadvertent Modification of the Stratosphere was established by the Federal Council for Science and Technology and the Council on Environmental Quality. This Task Force concluded that concerns about inadvertent ozone reduction were well founded, and that research efforts in this area should be accelerated. Supporting these conclusions, the Interdepartmental Committee for Atmospheric Sciences' Panel on Inadvertent Modification of Weather and Climate made additional recommendations in 1975 for increased research and additional measurements in upper atmospheric research.

In the 1976 NASA Authorization Act (Public Law 94-39), NASA is directed by Congress to develop and implement a comprehensive program of research, technology, and monitoring of the phenomena of the upper atmosphere aimed at improving basic scientific understanding of the upper atmosphere and the methods needed to maintain its chemical and physical integrity. The Act directs NASA to arrange for participation by the scientific and engineering community in planning and carrying out appropriate research, in developing necessary technology, and in making necessary observations and measurements. Efforts are also to be made to enlist the support and cooperation of cognizant scientists and engineers of other countries and international organizations. The interests of Congress were reiterated in 1977 in the Clean Air Act Amendments of 1977 (Public Law 95-95), where NASA is directed to continue programs in research, technology, and monitoring of the stratosphere for the purpose of understanding the physics and chemistry of these regions and for the early detection of potentially harmful changes of ozone.

To accomplish these objectives, NASA established the Upper Atmospheric Research Program in the Office of Space Science with cooperation of the Office of Space and Terrestrial Applications. Within this program, a Program Plan and a Measurement Strategy have been developed with the active participation of the NASA Stratospheric Research Advisory Committee (SRAC), a committee composed of experts from universities and other institutions who have demonstrated competence in various areas of atmospheric science.

The Measurement Strategy developed by the SRAC points strongly to the need for a continuing series of upper atmosphere research satellites to follow NIMBUS–G (1978), SAGE (1979), SME (1981), and HALOE (1982) to make dedicated long-term global measurements of the stratosphere, mesosphere, and lower thermosphere over extended time periods. The contributions to be made by the Space Shuttle AMPS program and ground-based, balloon-borne, and rocket-borne measurements are also addressed, but SRAC has concluded that each of these elements must be complementary to a long-term satellite observational program.

The National Academy of Sciences' Panel on Atmospheric Chemistry (1976, 1977), the Committee on Stratospheric Change (1976), and Geophysics Research Board (1977) have all made recommendations for specific long-term atmospheric measurements. They have also emphasized the importance of long-term, coordinated global atmospheric measurements toward improvement of scientific knowledge about upper atmospheric behavior.

It is with this background that the present Science Definition Group was established by NASA Headquarters. During the period November 1977 to May 1978, monthly meetings of the SDG were held to explore the scientific value of a satellite program devoted largely to remote sensing observations of the upper atmosphere. As described in the following sections, the SDG has developed a balanced research program involving satellite measurements and extensive theoretical and model analysis that it believes will meet the needs of the period 1983 to 1988 for obtaining knowledge necessary to understand the processes influencing the chemistry and dynamics of the upper atmosphere.

III. Scientific Background

The Earth's upper atmosphere is affected by many different processes that influence its overall chemical composition, energy budget, and dynamical behavior. In these regions, there is a continual interplay between solar radiation, atmospheric photochemistry, thermal radiative emission, turbulent diffusion, and dynamic motions. The balance between these different processes leads to the distinctive characteristics identifying the stratosphere, mesosphere, and thermosphere (see Fig. 1).

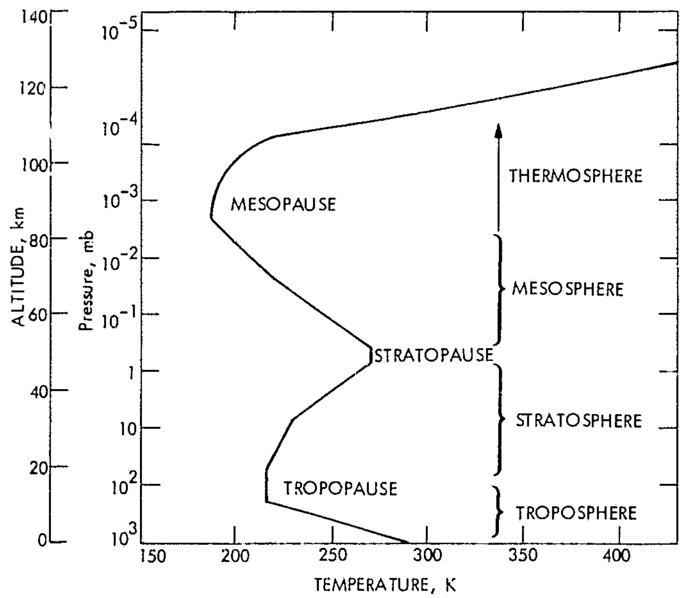

Fig. 1. Temperature structure of the atmosphere and nomenclature for those regions defined by the temperature structure. Also shown is the pressure-height relationship (from the U.S. Standard Atmosphere, 1976, for average conditions at 45°N latitude)

In this report, primary emphasis is given to scientific problems related to the structure and behavior of the regions between 10 and 120 km; that is, the stratosphere, mesosphere, and lower thermosphere. For the present purposes, discussion of the various processes influencing these regions can best be presented by considering separately the topics of radiation, chemistry, and dynamics. Much of the complexity of the upper atmosphere arises from couplings between these diverse processes.

In the final paragraphs of this section, the relationships between the general behavior of the upper atmosphere are discussed in terms of weather and climate.

A. Radiation

Solar radiant energy at visible wavelengths passes through the upper atmosphere with little attenuation. It is only at shorter and longer wavelengths (the ultraviolet and infrared portions of the spectrum) that substantial absorption takes place. Most of the solar flux in the far ultraviolet at wavelengths less than 175 nm is absorbed by N_2 and O_2 in the thermosphere and mesophere, yielding ionization, dissociation, and excitation products that profoundly influence the temperature and compositional structure of these regions.

At longer wavelengths, 175 to 310 nm, the solar radiant flux is absorbed by O_2 and O_3. The absorption by O_2 leads directly to the formation of atomic oxygen and thereby initiates the chemical chain leading to the formation of ozone, the most important minor constituent of the upper atmosphere. Absorption of solar UV radiation by ozone, on the other hand, leads both to ozone dissociation and atmospheric heating.

The energy budget of the upper atmosphere is principally determined by the balance between the heating associated with solar UV absorption by ozone and infrared thermal emission by O_3, CO_2, and, to a lesser extent, H_2O. The vertical temperature profile of the stratosphere is dominated by the presence of a large temperature inversion between 20 km and 50 km altitude established by ozone absorption (see Fig. 1). The heating rates due to atmospheric trace molecular constituents are shown in Fig. 2. Other heat sources, such as the dissipation of tidal or gravity waves and joule or particle heating, also contribute substantial energy in the mesosphere, but their quantitative analysis is not so straightforward as that for radiant heating and cooling.

The stratosphere and lower mesosphere are in approximate thermodynamic equilibrium. In the mesosphere and thermosphere, the conditions necessary for local thermodynamic equilibrium (LTE) gradually break down with increasing altitude, and individual radiative emission processes must be evaluated to determine temperatures and radiant energy fluxes. Observations of CO_2, O_3, NO, and NO^+ emissions in the 4-μm and 15-μm range, for example, show that important non-LTE processes are often present above 80 km.

Dynamic processes also contribute to thermal structure in an important manner. Horizontal gradients in gas temperature set by the solar radiative heating, for example, establish a pattern of dynamic motion in the atmosphere whose thermodynamic consequence is a strong departure from radiative equilibrium in the lower stratosphere and near the mesopause.

B. Chemistry

A qualitative understanding of the chemistry of the sources, sinks, and budgets of most upper atmospheric constituents now exists. Discussion of the chemistry of this region can be focussed on studies of families of constituents, the most important of which contain oxygen, nitrogen, hydrogen, chlorine, and sulfur. These chemical families are similar in that they contain three basic types of species: source molecules that are relatively stable compounds, radicals that are short-lived derivatives of the source molecules, and sink molecules that are the chemically evolved stable forms of the radicals. Concentration profiles of selected upper atmospheric minor species are shown in Fig. 3.

Stratospheric odd nitrogen (NO_x) arises mainly from the attack of $O(^1D)$, a photochemical product, on N_2O, which is

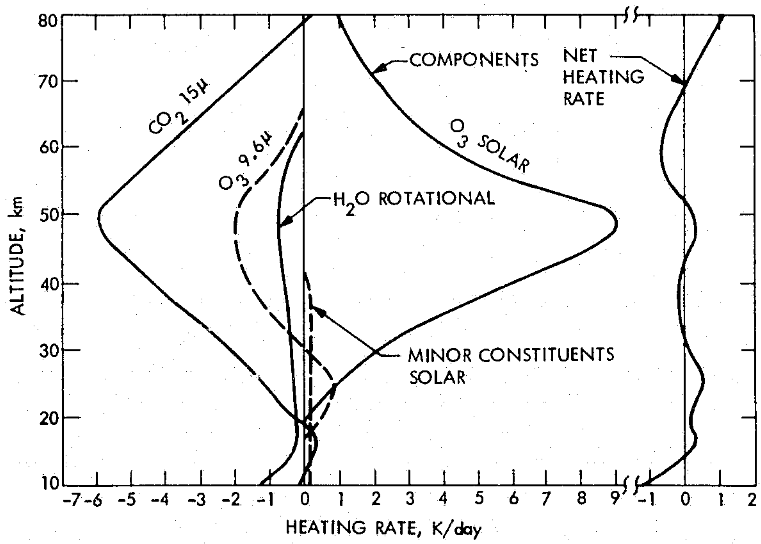

Fig. 2. Atmospheric heating rates

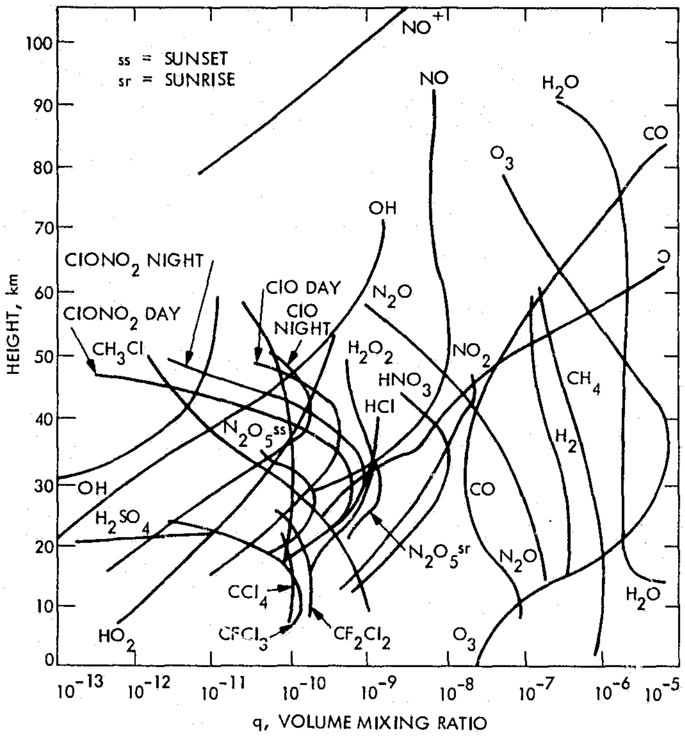

Fig. 3. Concentration profiles of minor species

produced by bacterial denitrification in soils and the ocean. The major sinks for NO_x are thought to be diffusion to the troposphere (followed by rainout of soluble HNO_3) and photodissociation of NO in the upper stratosphere (followed by reaction of N with NO to form N_2). In the mesosphere, the situation is more complex since odd nitrogen is produced from a variety of ionization and dissociation processes involving NO and N_2.

Hydrogen oxides are formed in the stratosphere and mesosphere by the reaction of $O(^1D)$ and H_2O. Destruction occurs principally by reaction of OH and HO_2 to reform H_2O. The water vapor budget seems to be controlled by two main processes: oxidation of CH_4, and upward transport from the troposphere. With regard to the latter process, vertical transport of water vapor into the stratosphere is thought to occur mainly in tropical regions through cumulus convection and the action of slow vertical motions associated with the rising branch of the global scale Hadley circulation cell. The slow rising motion carries the water vapor through the relatively cold tropopause, resulting in water vapor mixing ratios in the stratosphere that do not exceed the tropical tropopause saturation value. Within the stratosphere and mesosphere, the loss of water vapor is controlled by photodissociation in the upper mesosphere followed by upward diffusion of H to the thermosphere and eventual evaporative escape from the earth's gravitational field.

The budget of chlorine is uncertain. The major sources are linked to the photolysis of CCl_4 and CH_3Cl. Man-made $CFCl_3$ and CF_2Cl_2, photolyzed in the stratosphere, are increasingly important sources of chlorine. Other halocarbons such as CH_3CCl_3 (methyl chloroform) may also be significant. The only known sink for Cl_x is diffusion to the troposphere followed by rainout of HCl.

The atmospheric sulfur cycle is also uncertain. Theories suggest that sulfur compounds emitted at ground level in both natural and anthropogenic processes diffuse into the stratosphere where they are oxidized, giving sulfur trioxide, which later reacts in the presence of water to form sulfuric acid. It is believed that sulfuric acid molecules act as condensation nuclei leading to the growth of aerosols, which are the principal components of the stratospheric Junge layer(s). Loss of sulfur occurs when the heavier aerosols gradually settle out of the stratosphere into the troposphere.

C. Dynamics

The dynamics of the atmospheric regions below 30-km altitude are reasonably well understood from observational data obtained with the global radiosonde network, from extensive numerical results given by general circulation models, and from transport tracer studies. Above 30 km, our knowledge of the dynamical character of the atmosphere is rather poor owing to the lack of adequate observational data and the difficulty of creating suitable numerical models capable of reproducing the coupled effects of solar and thermal radiation, minor species chemistry, and dynamical motion.

In discussing the circulation of the upper atmosphere, it is convenient to refer to zonally-averaged motions and the departure from this mean, which are called waves. The mean meridional winds are torroidal circulations characterized by one or more cells between the two poles. The mean circulation in the lower stratosphere is driven by the absorption of solar radiation in the lower layers of the tropical troposphere. In this region the mean circulation is indirect (rising motions in the colder regions) and is maintained by energy and momentum transported from below. Examples of calculated mean meridional circulations are given in Fig. 4.

In the upper stratosphere and lower mesosphere there is direct circulation (rising motions in warm regions) with rising motions over the summer pole, a meridional drift at high levels into the winter hemisphere, and sinking air over the winter pole. The Coriolis torque acting on this meridional flow creates mean easterlies in the summer hemisphere and westerlies in the winter hemisphere. These mean zonal motions have annual variations as the summer and winter poles

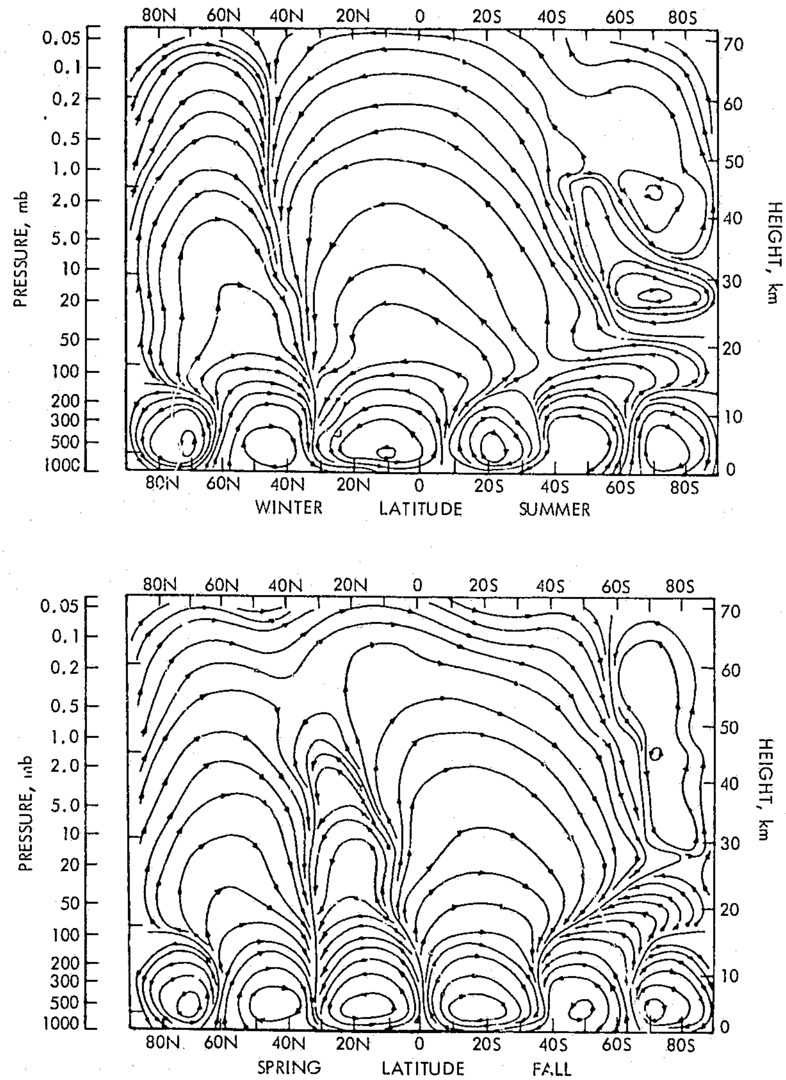

Fig. 4. Mean meridional circulation patterns for the solstices and equinox (from Ref. 5)

exchange position. In addition, a semiannual oscillation of zonal flow in the stratosphere and lower mesosphere is also observed, with maximum westerlies just after equinox and maximum easterlies just after solstice. A strong oscillation of zonal wind, the "quasi-biennial oscillation", is also seen in the tropical lower stratosphere, having an irregular period that averages at about 26 months. More irregular winds are also present, exhibiting short-term and year-to-year variations.

The mean atmospheric flow is supplemented by waves that have a significant role in upper atmospheric processes. In the extratropical regions up to 80 km, planetary Rossby waves are of greatest importance. In the tropics, tropical wave modes, the mixed Rossby-gravity waves and the Kelvin waves assume dominance. Above 80 km, atmospheric tides and gravity waves become important, containing as much energy as the longer time scale motions.

D. Weather and Climate

Weather and climate are among the most important parts of man's environment. The role of the upper atmosphere in the modification of these parameters is twofold. The first is the role of the stratosphere in modifying the temperature of the troposphere. The global mean surface temperature calculated by simple one-dimensional climatic models has been found to be sensitive to stratospheric radiative processes. However, dynamic and compositional coupling are also likely to be of considerable importance in linking stratospheric change to tropospheric change. First, tropospheric planetary waves significantly influence the longitudinal variations of surface climatic parameters. Their sources are believed to be primarily in the troposphere, but they propagate upward into the stratosphere where they are partially absorbed by radiative dissipation and partially reflected downward. Changes in stratospheric structure are likely to modify the altitude and degree of downward reflection and so, in principle, to modulate surface climate. This effect is likely to be small, but it is of intrinsic scientific interest because it requires improved understanding of the planetary-wave coupling between troposphere and stratosphere.

Compositional coupling is most likely to involve changes in motion and thermal structure in the 10- to 20-km region. One very important, but poorly understood, question is the coupling between tropospheric and stratospheric water vapor concentrations. As mentioned previously, stratospheric water vapor concentrations are thought to be controlled by the saturation mixing ratio at the tropical tropopause. If this is so, a long-term temperature increase of the tropical tropopause by 3 K might as much as double stratospheric water vapor concentrations. Such a change of tropopause temperature could result within the next 50 years as a result of increasing amounts of various trace gases in the troposphere; in particular, carbon dioxide and the chlorofluoromethanes.

Another role that the upper atmosphere might play in climatic change is that of a coupling medium linking solar "weather" to meteorological variables. As far as the upper thermosphere and magnetosphere are concerned, such connections are abundant, well-documented, and mainly understood, at least in principle. In the upper and lower atmosphere, however, the correlations become less obvious and the conceptual difficulties become greater, for it is necessary to suppose that extremely small energies are affecting huge masses of air. Thus, although over the past few years empirical correlations have been put forward, they have been viewed with suspicion by many scientists. Of course much of the controversy reflects the paucity of data and the lack of plausible mechanisms. However, if a relationship does exist, it likely will involve some coupling mechanism through the upper atmosphere.

Life on Earth is dependent on the interaction of the atmosphere, geologic events, solar radiation, and activities of different life forms. To trace the evolution of man and insure his future, it is essential to understand the interdependence of these complex phenomena. Nowhere is this more clearly illustrated than in the potential depletion of atmospheric ozone by human activities, and the accompanying harm to animal and plant life that may result from increased atmospheric penetration of solar ultraviolet radiation. Potentially harmful activities include the use of fertilizers and insecticides, aerosol sprays, aircraft emissions, and nuclear explosions. Natural events may also affect the atmosphere, e.g., energetic particles from the Sun can destroy ozone as can short wavelength radiation from nearby exploding stars.

While the destruction of ozone has focused the attention of the scientific community and the general public on the upper atmosphere and its importance to man, there may be other instances where man's activities or natural phenomena adversely affect the upper atmosphere. The problem is one of the most complex in present day science, and encompasses several disciplines. In turn, it is part of the larger problem of planetary atmospheric evolution, life on other planets and solar-terrestrial relations. The interdisciplinary nature of the problem comes about because the interactions involve the Sun, atmosphere, geologic processes, and life forms. Energy from the Sun, outgassing from the Earth's interior, and interchange of gases between life forms and the atmosphere, as well as between ocean and atmosphere, are the instruments of these interactions. The objective of the UARS program is to examine some of these important questions, especially with regard to the role of the upper atmosphere in the overall picture.

IV. Objectives of the Program

The primary objective of the Upper Atmosphere Research Satellite Program is the study of the physical processes acting within and upon the stratosphere, mesosphere, and lower thermosphere. Our present knowledge of this region of the atmosphere is derived largely from various in situ measurements (balloons, rockets, aircraft) that sample the medium directly, as well as ground-based observations of optical, infrared, and radio wave emissions. These results have provided an initial view of the complex interactive processes acting within the upper atmosphere. To probe more deeply into the actual mechanisms, a far more extensive program of study based upon global measurements over an extended period of time is required.

With the recent development of remote sensing technology, it has become apparent that measurements from spacecraft are a practical means of gathering infomation about atmospheric internal structure (trace constituents, dynamical motions, radiative emission, thermal structure, and density) as well as the external influences acting upon this region (e.g., solar radiation, tropospheric conditions, magnetospheric particles, electric fields). The NIMBUS spacecraft, for example, have already provided measurements of atmospheric temperature profiles up to the mesopause and stratospheric ozone concentrations.

A major conclusion of the present study is that current technology can provide the advanced instruments necessary for a comprehensive program of scientific measurements that are needed to resolve a number of crucial questions pertaining to the chemistry and physics of the atmosphere.

Within the context of the overall program objective of studying the physical processes of the upper atmosphere, three long-term goals for the UARS Program have been identified by the Science Working Group:

(1) To understand the mechanisms that control upper atmosphere structure and variability.

(2) To understand the response of the upper atmosphere to natural and anthropogenic perturbations.

(3) To define the role of the upper atmosphere in climate and climate variability.

Substantial progress in achieving these goals will be possible only if there is a strong and continuing interaction between theorists and experimenters to determine specific research objectives during the lifetime of the UARS Program. In addition, there is an urgent need for an active program of theoretical research to proceed in parallel with the measurement program. As discussed later, the major emphasis of the theoretical work should be the improvement of knowledge of the relevent physical processes acting in the upper atmosphere and validation of models of atmospheric behavior.

The long-term goals given above are supported by four specific topics of research: the atmospheric energy budget, atmospheric chemistry, atmospheric dynamics, and atmospheric coupling processes. In the following sections, the scientific aspects of each of these topics are discussed. At the end of each section, key scientific questions are given to summarize the outstanding gaps in our present knowledge. Later, these key questions are used to define sets of measurements appropriate for the initial UARS missions.

A. Energy Input and Loss in the Upper Atmosphere

Central to the study of the upper atmosphere is its overall energy balance. The two most important items in the general energy budget are the absorption of solar radiation by ozone, and radiative cooling in the 15-μm band of CO_2. Additional processes, including transport and other atmospheric emissions, provide complex couplings that affect atmospheric chemistry and dynamics. In this section, emphasis is given to the radiative sources and sinks of atmospheric energy.

1. Radiative sources and sinks. Virtually all of the solar irradiance in the spectral interval 120 to 310 nm is absorbed between the tropopause and the lower thermosphere, where it provides the dominant heat source for the overall energy budget. As a consequence, solar radiation in this spectral band determines the general thermal structure and the subseqeunt dynamics of this region. In addition, a portion of this spectral interval also is responsible for photochemical processes affecting trace concentrations.

The solar spectrum between 120 and 350 nm can be divided into two distinctive bands. Between about 120 and 150 nm, the spectrum is dominated by chromospheric emission lines superimposed on a weak continuum background, and at longer wavelengths continuum emission from the lower photospheric layers dominates the spectrum. Since, in general, the emission from the chromosphere varies significantly as a function of solar activity, while that from the photosphere does not, activity-induced variations in UV emissions occur predominately in the shorter wavelength regime (120 to 150 nm).

The largest percentage increase observed during a solar flare in the 120- to 300-nm range is in the Lyman-alpha line of neutral hydrogen, e.g., about 16 percent for a class 3b flare. Similarly, the variations associated with the 27-day rotational period decline exponentially with increasing wavelength, being about 36 percent at 120 nm and about 1 percent at 300 nm. At 175 nm, this variability is comparable to that due to the 6.5-percent annual variation associated with the changing Sun-Earth distance.

One of the least understood and one of the most important questions in upper atmospheric physics is whether or not the solar UV flux changes over the 11-year solar cycle. Some measurements indicate a factor-of-two variation near 120 nm, but this result has, as yet, not been verified. It is well established that the solar flux below 120 nm varies significantly over a solar cycle because of the strong effect of solar activity on the emission from the chromospheric-coronal interface.

The lower thermosphere is heated in the sunlit hemisphere through absorption by molecular oxygen of solar radiation in the spectral interval of 150 to 200 nm. Absorption of solar radiation in the Hartley continuum (200 to 300 nm) by ozone is responsible for the radiative energy input to the mesosphere and stratosphere. Although the number density of ozone is a maximum in the lower and middle stratosphere, the absorption per unit mass is a maximum at the stratopause. Very little direct absorption of solar radiation takes place in the lower stratosphere.

The stratospheric aerosol layer (the Junge layer), which reaches its peak concentration in the 15- to 25-km region, can act as a local heat source for the ambient atmosphere as a result of the absorption of solar radiation and infrared radiation emitted from the Earth's surface and surrounding atmosphere. Studies indicate the aerosol layer consists mostly of sulfate particles present in low concentrations during long periods, even without volcanic eruption. Adequate knowledge of aerosol concentration profiles, composition, and physical properties is presently lacking. This information is necessary to assess the influence of the aerosol layer on the radiation balance.

Most polyatomic constituents in the upper atmosphere emit radiation in the thermal infrared. The principal contributors to the radiative cooling of the 10- to 120-km region of the atmosphere are CO_2, O_3, and H_2O. It is found that radiative relaxation times for the molecular species of the stratosphere and lower mesosphere are sufficiently long so that these species are in approximate thermodynamic equilibrium, and emission calculations can be based on the assumption of local thermodynamic equilibrium (LTE). Cooling is dominated by the 15-μm band of CO_2 with smaller but nonnegligible contributions to the 9.6-μm O_3 bands. The 6.3-μm and long-wave rotation bands ($\lambda > 16$ μm) of H_2O contribute one-tenth as much cooling as does ozone.

In the mesosphere and thermosphere, there are a variety of discrete emission processes that must be considered where radiative cooling rates are evaluated. Observations of CO_2, O_3, and NO and NO^+ emissions in the 4- to 15-μm range indicate that these species have important nonthermal processes at altitudes above 80 km. In addition, emissions in the visible and near infrared from OH and O_2 $(^1\Delta_g)$ represent substantial cooling in narrow altitude ranges. These emissions exhibit considerable latitude and temporal dependence, with the largest effects occurring in the auroral zones.

2. **Other energy sources.** Reliable information concerning atmospheric heating through nonradiative processes is sparse. It is thought that heating associated with nonlinear dissipation of tidal and gravity wave energy may be present throughout the atmosphere. In the stratosphere, substantial contributions may arise from large-scale meteorological phenomena even though the transmission of such energy from the troposphere to the stratosphere and higher regions may be small. Between 80 and 100 km, for example, estimates of wave dissipation indicate a contribution exceeding 10 percent of the total local heat input. Further, tidal-wave dissipation is expected to significantly increase the equilibrium eddy diffusion coefficient in the upper mesosphere and lower thermosphere, affecting the vertical transport of thermal energy in a region of strong temperature gradient.

At high geomagnetic latitudes, atmospheric heating by auroral electrons and global scale electric current systems is important within the upper mesosphere and lower thermosphere. During periods of relative calm within the magnetosphere, the power dissipated within the auroral zones by the two processes is of the order 10^{10} watts while up to 10^{12} watts is dissipated during periods of large magnetospheric disturbance. It is not thought that such dissipation directly affects processes within the stratosphere, although the possibility of an indirect modulation effect upon radiant energy passing through the higher atmospheric regions cannot be ruled out at the present time.

3. **Key scientific questions:**

(1) What is the solar radiation spectrum and its temporal variation between wavelengths of 120 and 400 nm?

(2) What is the vertical attenuation of solar radiation in the wavelength range of 120 to 400 nm at altitudes between 10 and 120 km?

(3) What is the global morphology of atmospheric radiative heating?

(4) What is the global morphology of radiative cooling?

(5) How accurately can theoretical radiative equilibrium models predict atmospheric temperatures below 70 km?

(6) What influence do discrete emission processes have upon the thermal balance of the mesosphere and lower thermosphere?

(7) What is the sensitivity of the stratospheric radiation budget to tropospheric parameters, such as cloud-top temperature?

(8) To what extent do energy sources associated with magnetospheric electric fields and particle precipitation affect the thermal balances of the lower thermosphere and upper mesosphere?

(9) What is the solar radiation spectrum and its temporal variation at X-ray wavelengths?

B. Atmospheric Chemistry

1. **Sources, sinks, and budgets.** In general, a qualitative understanding of the sources, sinks, and budgets of most of the known constituents of the upper atmosphere now exists. Discussion of the relevant chemistry can be divided into studies of a few families of constituents, such as those containing nitrogen, hydrogen, and chlorine. These families contain three basic types of molecules (see Fig. 5). The source molecules, which are relatively stable compounds, are usually evolved from biological, geological, or anthropogenic processes. Examples are H_2O, N_2O, CH_3Cl, CCl_4, and CH_4. The radicals are short-lived derivatives of the source molecules that participate in rapid chemical reactions, such as the catalytic

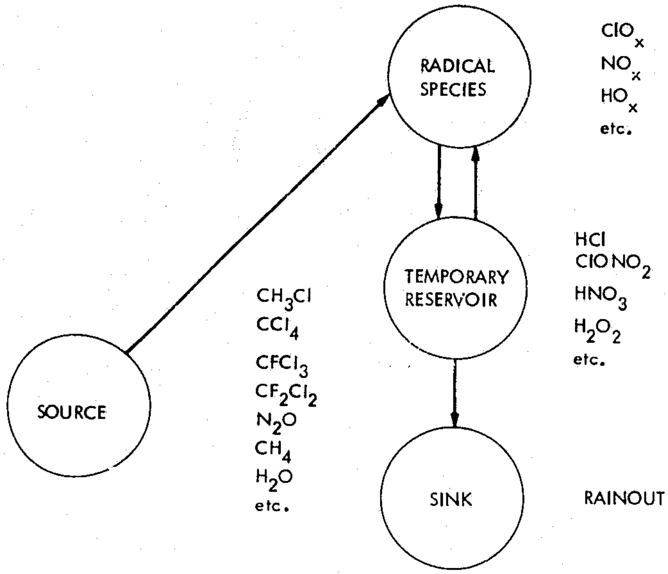

Fig. 5. Schematic representation of stratospheric chemical systems (from Ref. 2)

cycles of ozone destruction. Examples are the simple oxides of N, H, and Cl, and the atoms themselves. Finally, the temporary reservoir/sink molecules are the more stable forms into which the radicals can be temporarily recombined, and which may also be precursors of molecules removed by heterogeneous reactions or rainout. Examples of these are HCl, HNO_3, and $ClONO_2$.

The chemistry of the radical species is presently under intensive study with simultaneous in situ measurements of many chemically interconnected species. A major goal of the proposed UARSP measurements will be the global observation of selected molecules, reactive species (radicals), and reservoir/sink molecules for the important chemical families. Brief descriptions of present knowledge of the N, H, and Cl families is given below. Other potentially important species, such as the compounds of sulphur, bromine, and fluorine, may eventually assume equivilant prominence.

a. Nitrogen oxides. Stratospheric odd nitrogen (NO_x) is thought to come mainly from the attack of $O(^1D)$ on N_2O, which is produced by bacterial denitrification in soils and oceans. The major sinks for NO_x are thought to be diffusion to the troposphere, followed by rainout of soluble HNO_3, and photodissociation of NO in the upper stratosphere followed by reaction of N with NO to form N_2.

Mesospheric odd nitrogen is produced from a variety of ionization and dissociation processes, and also from direct dissociation of N_2. The odd nitrogen from these processes is effectively screened from the stratospheric odd nitrogen budget by NO photodissociation. However, since there is no photodissociation in the polar winter night, mesospheric processes may provide odd nitrogen to the stratospheric budget in this region.

b. Hydrogen oxides. The hydrogen oxide budget is thought to be driven by a near-photochemical equilibrium between formation by reaction of $O(^1D)$ and H_2O, and destruction mainly by reaction of OH and HO_2 to reform H_2O. The two major sources of stratospheric water are transport from the troposphere and oxidation of methane (CH_4). The rapid decrease in temperature from the ground to the tropopause causes an effective cold trap to be formed, limiting the tropospheric contribution to stratospheric water vapor to a few (~3) parts per million.

The mechanism of transport of water vapor from the troposphere to the stratosphere may include a variety of processes, such as small-scale diffusion, thunderstorm penetration, or the rising part of a Hadley circulation cell. The relative efficiency of these processes is uncertain. Methane provides a means of transporting hydrogen into the stratosphere without the effect of rainout. Eventually, methane oxidation must yield CO_2 and H_2O. This occurs in the middle and upper stratosphere, and should provide about 3 ppmv of H_2O, seen as an increase in mixing ratio with altitude. The loss processes for water vapor include condensation in the troposphere and dissociation in the upper mesosphere, followed by escape of a fraction of the H atoms.

c. Chlorine. The budget of chlorine is less well known. The major sources are thought to be CCl_4 and CH_3Cl, which are transported to the stratosphere where photolysis produces chlorine atoms. Direct injection of HCl into the stratosphere is thought to be less important because of its high solubility in water. Man-made $CFCl_3$ and CF_2Cl_2, photolyzed in the stratosphere, will provide an increasing fraction of the injected chlorine. Other halocarbons such as CH_3CCl_3 (methyl chloroform) may be significant sources. The only known sink for the resultant chlorine is diffusion to the troposphere followed by rainout of HCl.

d. Sulfur. The atmospheric sulfur cycle is intimately connected with the formation of stratospheric aerosols. Studies of the chemical cycle are complicated by the effect of direct volcanic injections of aerosol particles into the stratopshere as well as direct injection of sulfur compounds, which are precursors to aerosol formation. Theories of the quiet-time sulfur cycle indicate that sulfur compounds emitted at ground level in both natural and anthropogenic processes diffuse into the stratosphere where they are oxidized, giving sulfur trioxide, which later reacts in the presence of water to form sulfuric acid. It is believed that sulfuric acid molecules act as condensation nuclei leading to the growth of stratospheric aerosols, which are observed to exist in a 75-percent solution with water and are the principal component of the Junge layer. Ammonium sulphate particles have also been found in the stratosphere, but the mechanisms for conversion from the gaseous sulfur state are not known. Sulphur dioxide and ammonia vapor have not been detected in the stratosphere by current state-of-the-art instrumentation. These very low concentrations indicate that the conversion takes place very rapidly. Certainly water vapor, but also ozone and perhaps nitric acid, may take part in these processes. The sink for sulphur occurs when the heavier aerosols settle out of the stratosphere into the troposphere forming a dilute "acid rain," which returns the sulphur to the earth's surface.

e. Ion chemistry. Calculations indicate generally that processes involving ionic species in the reactions that determine the balance of radical species are relatively unimportant. This is largely because of the small concentrations of ionic species in the stratosphere. There is at least one notable exception to this generalization, however: the production of NO in the thermosphere and mesosphere. Any ionization of atmospheric species, especially O and N_2, has a high probability of producing, at the end of a variety of reaction chains, a nitric oxide molecule. It is this type of process that is believed to be responsible for the reduction of high-altitude ozone concentrations following solar proton events at high magnetic latitudes. It is likely that significant production of nitric oxide also occurs because of relativistic electron precipitation events, cosmic rays, and auroral processes.

These ionization events also produce odd oxygen at the rate of 1 or 2 per ionization. However, this effect is overwhelmed by the destruction due to odd nitrogen because of the catalytic nature of the reactions.

2. **Perturbations.** A number of influences arising from sources outside the upper atmosphere are known to occur. Among these are the penetration of energetic protons to stratospheric altitudes in solar proton (polar cap absorption or PCA) events, electron precipitation to the mesosphere in relativistic electron precipitation (REP) events, volcanic explosions (whose effluence can reach 50 km altitude), and man-made perturbations, such as atmospheric nuclear tests and chlorofluoromethane (CFM) release. All of these can have significant impact upon upper atmospheric minor constituents. The theory of the coupling of these radicals with the overall scheme of minor constituent chemistry is useful for building models of the response of the atmosphere to external perturbations. Such models can then be tested against measurements of key chemical species during the course of an actual event. These perturbations provide a more sensitive evaluation than is provided by the changes associated with the ambient, quiet time atmosphere.

An additional reason for studying atmospheric perturbations lies in their potential contribution to the global budgets of the various trace species. Studies of a large solar proton event in August 1972, for example, have shown the presence of large ozone changes in the upper stratosphere with the polar caps. Although simultaneous measurements of NO were lacking, calculations indicate that the ozone reduction was consistent with an NO enhancement caused by proton dissociation of N_2. The overall effect of large proton bombardments, as well as the more numerous small events, on the long-term odd nitrogen budget is presently not known.

Large volcanic eruptions may affect the stratospheric chlorine budget within a year or so subsequent to the eruption. Other processes, such as variations in the galactic cosmic ray background, nuclear explosions, solar cycle variations of incident UV radiaiton, and man-induced or natural variation in the biospheric production of source molecules may also make their contributions to the various chemical budgets.

3. **Key scientific questions:**

(1) What is the global distribution of ozone, and what are its temporal variations?

(2) What is the global distribution of the source molecules (e.g., N_2, CH_3Cl, CH_4, CF_2Cl_2, and $CFCl_3$) of the upper atmospheric radicals?

(3) What is the global distribution of the molecules (e.g., HNO_3, HCl, H_2O_2, and N_2O_5) that serve as reservoirs (and/or sinks) for the upper atmospheric radicals (e.g., ClO_x, NO_x, and HO_x)?

(4) What is the global distribution of the radical families ClO_x, HO_x, NO_x?

(5) What are the diurnal variations of the radical and reservoir species, and what is the impact on the average chemical budgets?

(6) What are the processes by which the sources and reservoirs determine the mean radical concentrations? How variable are these processes in time and space?

(7) What is the response of the upper atmospheric chemical system to external perturbations?

(8) What are the roles of heterogeneous and surface reactions in the chemical and ionic processes of the upper atmosphere?

(9) What is the role of ion chemistry in determining the structure of the normally quiet upper atmosphere, and

the upper atmosphere during such perturbations such as solar proton events, relativistic electron precipitation, and nuclear explosions?

C. Dynamics of the Upper Atmosphere

The general circulation of the atmosphere can be expressed in complete form using field variables that give the atmospheric state. In practice, it is usual to employ zonally averaged quantities and their deviations, termed waves or eddies. The deviation fields can be Fourier-decomposed to give zonal wave components. With this convention, many of the problems of upper atmospheric dynamics concern the dynamics of the mean zonal flow, the dynamics of the planetary scale eddies, and the interaction between the mean flow and the eddies.

1. **Zonally averaged motions.** The overall circulation in the upper stratosphere and mesosphere is created primarily by the north-south differential in the heating of the ozone layer (centered at about 50 km) due to absorption of solar ultraviolet energy, and the subsequent infrared emission to space from carbon dioxide, ozone, and water vapor. The net radiative heating distribution (Fig. 6) has a strong seasonal dependence with maximum heating at the summer pole and maximum cooling at the winter pole. The differential heating drives a mean meridional circulation whose overall structure consists of rising motion near the summer pole, a meridional drift at high levels into the winter hemisphere, and sinking near the winter pole. The Coriolis torque acting on this meridional flow gives rise to mean zonal easterlies in the summer hemisphere and westerlies in the winter hemisphere, which are in approximate thermal wind balance with the zonal mean temperature field. Schematic cross-sections of the zonally averaged temperature and zonal wind component (mean zonal wind) from the surface to 75 km altitude at the solstices are shown in Figs. 7 and 8.

The mean zonal motions are not constant in time. The winds have an annual change of direction as the winter and summer poles exchange location. Global semiannual oscillation in the upper stratospheric and lower mesospheric zonal flow is also observed, with maximum westerlies occurring just after the equinoxes and maximum easterlies occurring just after the solstices. There is also a very strong oscillation of the mean zonal wind in the lower tropical stratosphere with a somewhat irregular period that averages at about 26 months, the so-called "quasi-biennial oscillation." In addition to these cyclic variations, there are a number of irregular short-term and year-to-year variations.

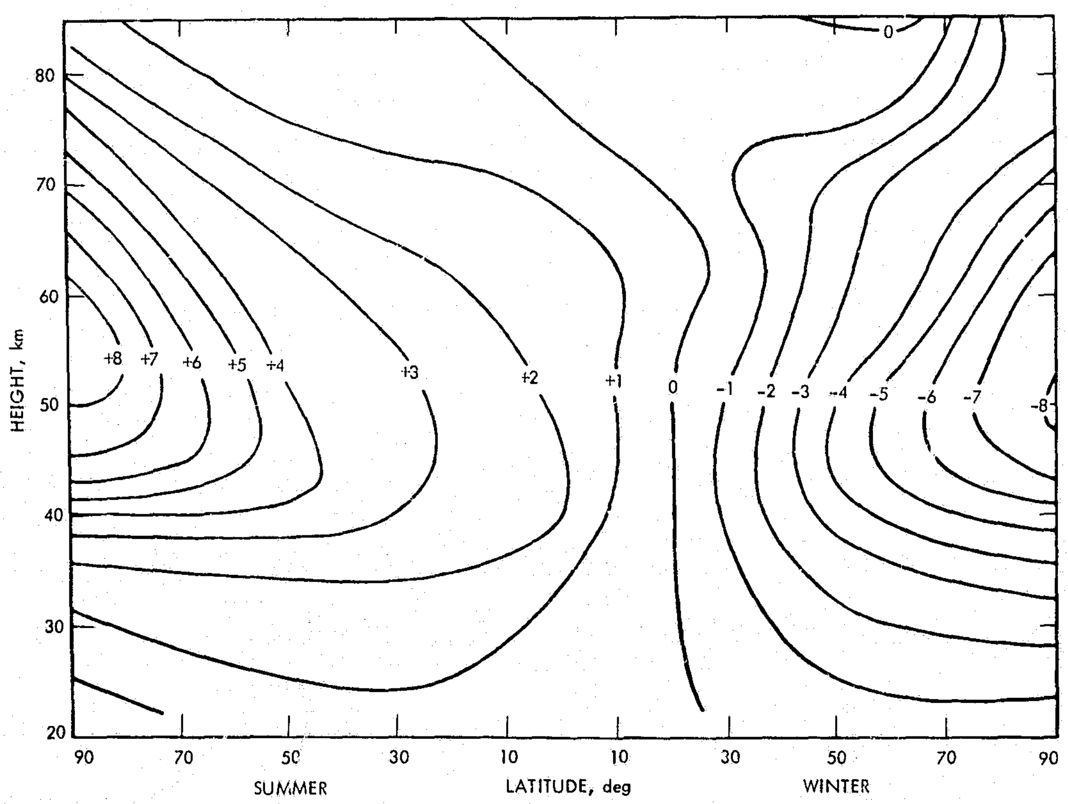

Fig. 6. Zonal mean "external" heating $^{-}J_e$ (K/day) for an atmosphere with standard horizontal mean radiative equilibrium temperature T_0 (z) (after Ref. 3)

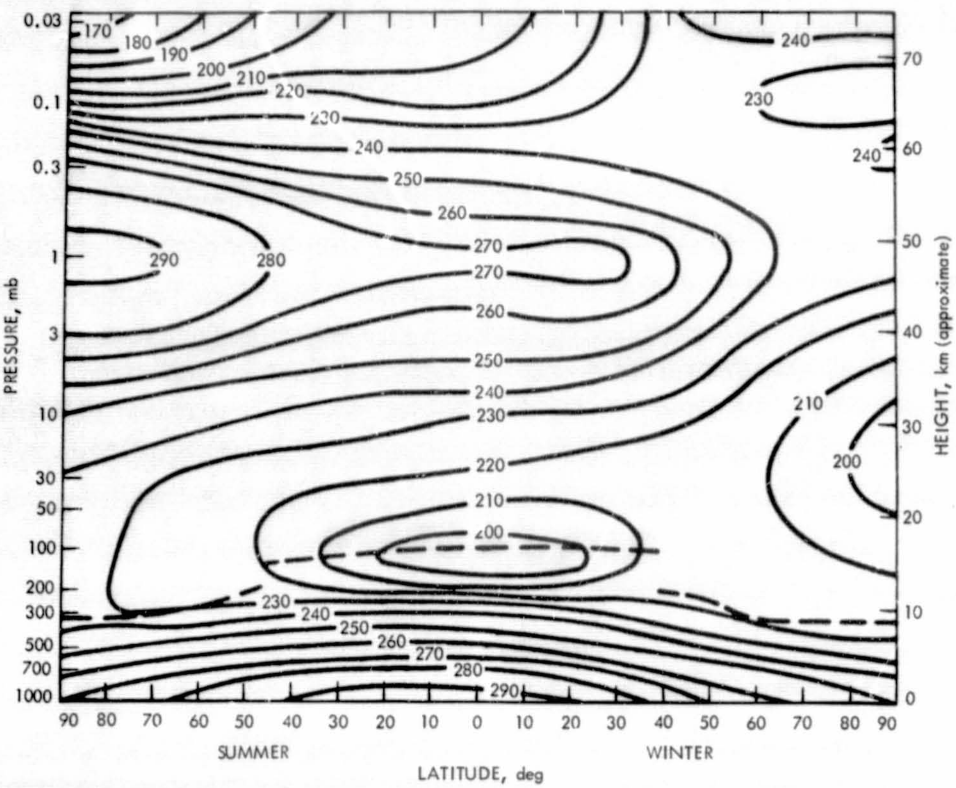

Fig. 7. Latitude-height section of zonal mean temperatures (K) at the solstices (after Ref. 4)

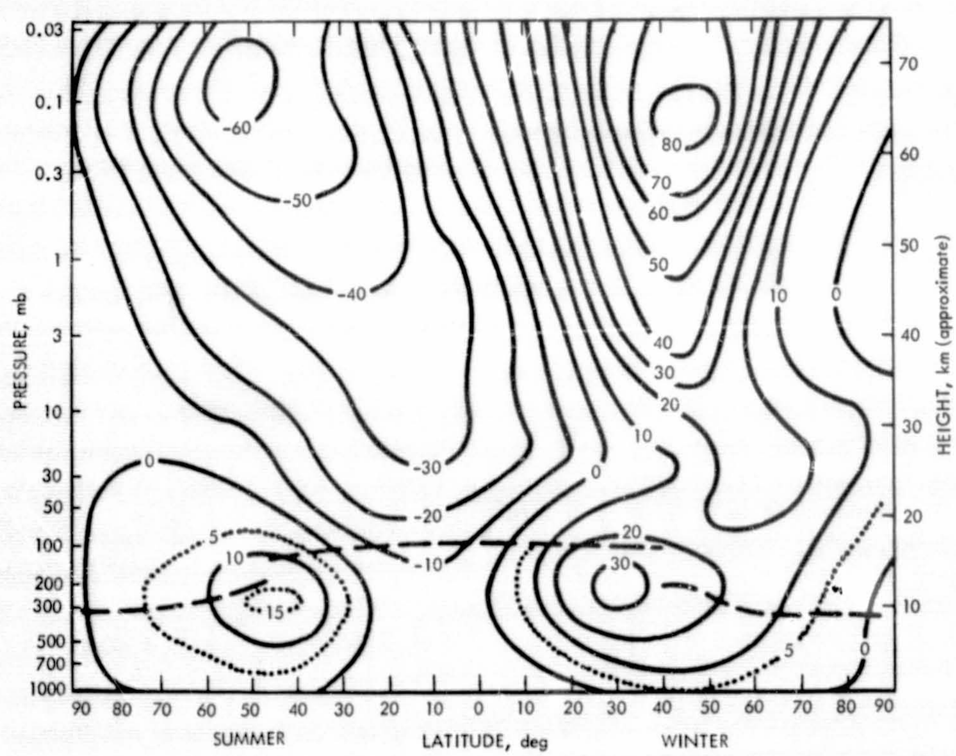

Fig. 8. Latitude-height section of the mean zonal wind (m/s) at the solstices (after Ref. 4)

Direct observation of the mean meridional motion is much more difficult than for the zonal motions, owing to the small magnitude of the zonally averaged meridional velocity compared to the relatively large deviations from the zonal average. Sufficient data do not exist to derive the mean meridional motion above about 30-km altitude, although models have produced mean meridional circulations that are consistent with observations in the troposphere and lower stratosphere. Modelled circulations for solstice and equinox conditions are shown in Fig. 4. Since the mean meridional motions are not in geostrophic balance, they cannot be derived directly from the density field, as can the mean zonal motions.

2. Wave or eddy motions. Wave dynamics have an important role in the upper atmosphere. In the extratropical atmosphere up to about 80 km, the waves of greatest importance are the planetary Rossby waves. These waves are nearly geostrophic and owe their existence to the latitudinal variation of the Coriolis parameter. Their observed vertical wavelengths are several tens of kilometers, and their horizontal scales are at least several thousand kilometers. These waves have comparatively large amplitude manifestations in the temperature field. They are of great importance to the general circulation of the stratosphere-mesosphere, to the transport of trace materials in the stratosphere, and are also the central driving mechanism for stratospheric warmings. A decomposition of a typical winter stratospheric circulation into its zonal mean and its planetary wave components is shown in Figs. 4, 9, and 10.

In the tropical regions, the Rossby waves are replaced by mixed Rossby-gravity waves and Kelvin waves as the modes of greatest importance. These waves have much stronger ageostrophic components, shorter vertical scales, and smaller temperature perturbations relative to a given velocity perturbation than the midlatitude Rossby waves. The observed characteristics of these mixed Rossby-gravity waves and Kelvin waves are given in Table 1.

Above about 80 km, tides and gravity waves contain as much energy as the longer time-scale motions.

3. Energetics. The energetics of the upper atmosphere vary significantly with altitude. The main features may be briefly described by noting that mean meridional circulations are driven by the differential heating that results from the absorption of solar energy and infrared cooling. The direct cells in the tropics are driven by absorption in the troposphere, with the resulting motions extending high into the stratosphere (see Fig. 4). The resulting meridional motions produce part of the mean zonal circulation through the action of Coriolis torques. The lower stratosphere derives part of its energy from upward propagating planetary waves. The upper

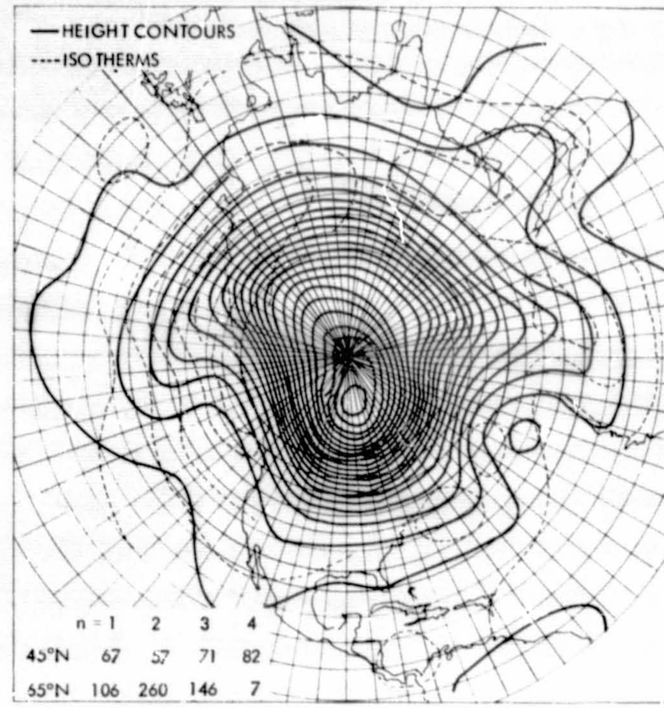

Fig. 9. Northern Hemisphere 50-mb chart for 1200 GMT, January 13, 1958. Height contours are given in meters, isotherms in °C. Amplitudes of wave numbers 1 through 4 are tabulated in meters at the bottom of the map (from Ref. 5)

stratospheric and lower mesospheric circulation is probably driven more by solar differential radiative heating. In the upper mesosphere, as in the lower stratosphere, the forcing that results from upward propagating planetary waves again probably assumes greater importance.

The convergence of eddy momentum is an important drive for many of the zonal circulations. Thus, although the momentum source for the semiannual wind oscillation is uncertain at this time, Kelvin waves are the most likely candidate, and the maintenance of the quasi-biennial oscillation is thought to be a result of mean flow interactions with Kelvin and mixed Rossby-gravity waves. Time variations in the zonal flow are apparent due to nonlinear forcing of the zonal mean circulation by vertically propagating planetary waves. Most prominent among these irregular variations are the major and minor high-latitude sudden stratospheric warmings that occur during the winter and spring in each hemisphere.

4. Tidal motions. The primary tidal components in the atmosphere are the solar diurnal and semidiurnal tides that are excited primarily by solar heating of ozone in the upper stratosphere and the mesosphere, and of water vapor in the troposphere. Typical observed tidal wind amplitudes are 1 to 2 ms^{-1} at 30 km, 5 to 10 ms^{-1} at 50 km and 40 ms^{-1} above

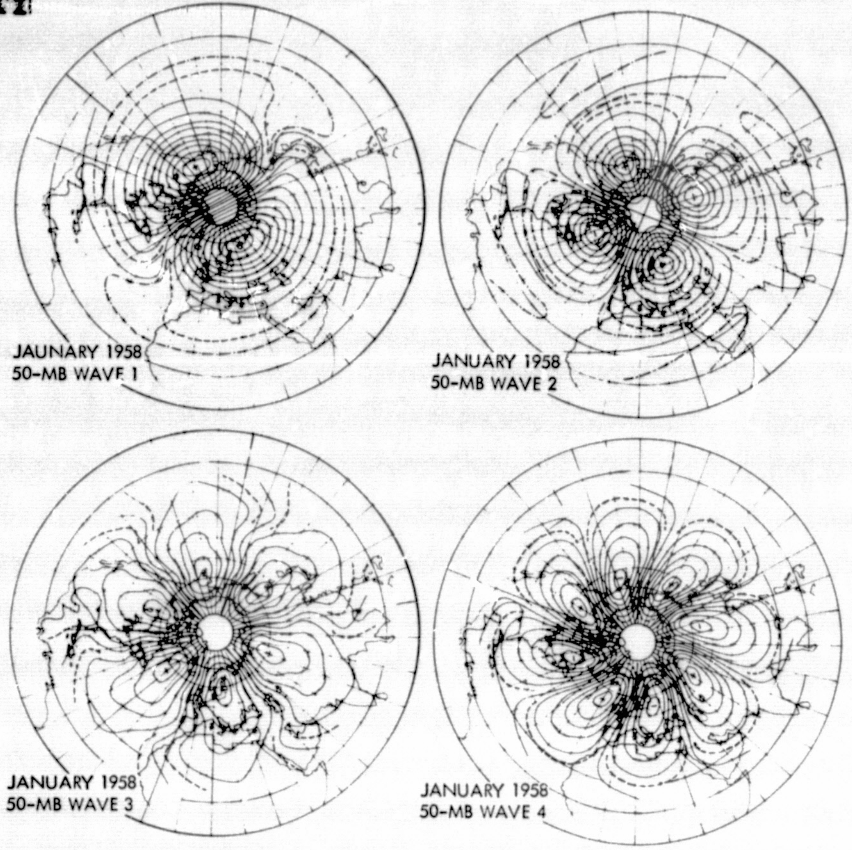

Fig. 10. 50-mb standing waves 1 through 4 for January 1958 (after Ref. 6)

Table 1. Description of vertically propagating wave modes in the tropical stratosphere

Parameter	Yanai and Maruyama	Wallace and Kousky
Theoretical description	mixed Rossby-gravity wave	Kelvin wave
Frequency ω (ground based)	$2\pi/4$–5 days	$2\pi/15$ days
Horizontal wavelength L	~10,000 km	~30,000 km
Zonal wavenumber k	~4	1–2
Vertical wavelength D	4–8 km	6–10 km
Average phase speed relative to ground	-23 m s^{-1}	$+25$ m s^{-1}
Average phase speed relative to zonal wind	-30 m s^{-1} (footnote a)	$+50$ m s^{-1} (footnote b)
Doppler-shifted frequency ω'	$2\pi/3$ days (footnote a)	$2\pi/8$ days (footnote b)
Amplitudes		
Zonal wind u^*	2–3 m s^{-1}	~8 m s^{-1}
Meridional wind v^*	2–3 m s^{-1}	0
Temperature T^*	~1°C	2–3°C
Geopotential height z^*	~30 m	~4 m
Vertical velocity w^*	~0.15 cm s^{-1}	~0.15 cm s^{-1}

[a] Near level of maximum westerly winds, where $U \sim 7$ m s^{-1}.

[b] Near level of maximum easterly winds, where $U \sim -25$ m s^{-1}.

60 km. Calculations based on tidal theory are in general agreement with observations, but there are some notable discrepancies (particularly between rocketsonde measurements of the diurnal tide and observations). Some observations of seasonal and shorter-term variability in the atmospheric tides, which theoretical models do not fully explain, have been made using ground-based techniques.

Tidal motions in the stratosphere and mesosphere may play an important role in affecting the mean motions and the transport of trace constituents in this part of the atmosphere. There have been suggestions that tides may affect the zonal mean flow in a significant manner. Also, interactions of semidiurnal tidal oscillations with interdiurnal variations of the polar vortex may affect dispersion of pollutants in the upper stratosphere on time scales of 6 to 12 hours, and space scales of 100 to 1000 km. Furthermore, the unstable breakup of tidal oscillations is thought to be a source of turbulence above 85 km. Aside from these effects of atmospheric tides, a valid description of tidal motions is clearly important since they provide a means to study the dynamic response of the upper atmosphere to the solar driving force, they are important to our understanding of the energetics of the atmosphere, and their strong presence in the upper atmosphere will have to be taken into account if we are to derive mean motions from observed radiances by the geostrophic method.

5. **Thermospheric circulation.** The global circulation in the thermosphere is dynamically active with large variations about a basic state. This is due primarily to the variable nature of the main forcings for thermospheric dynamics: heating due to absorption of solar EUV and UV radiation, heating due to auroral particle precipitation, joule heating due to the dissipation of ionospheric currents, momentum addition due to ionospheric convection, and the effects of tides and other disturbances that propagate upward from the lower atmosphere and are dissipated within the thermosphere. Most of these energy and momentum sources have seasonal, solar cycle, and geomagnetic storm time variations that greatly influence the thermospheric structure and circulation. The thermospheric circulation plays an important role in the global redistribution of energy, momentum, and changes in the neutral composition generated at high latitudes by auroral processes. Long-lived species produced in the aurora are transported to mid- and low-latitudes, where they diffuse downward to lower altitudes, thus affecting the neutral composition and heating rates of the mesosphere and perhaps even the stratosphere.

6. **Key scientific questions:**

(1) What are the relative roles of energy generation in situ (by solar heating) and tropospheric energy fluxes in maintaining the upper atmospheric circulation?

(2) What is the strength and variability of the low-latitude Hadley cell? How are its energy and momentum balances maintained?

(3) Through what mechanism does the semiannual wind oscillation in the equatorial upper stratosphere occur?

(4) What mechanism is responsible for the warm winter and cold summer mesopause?

(5) At what altitude do ageostrophic wave motions dominate geostrophic motions?

(6) What role, if any, do in situ instabilities play in the upper atmosphere?

(7) What is the influence of the aurora, thermospheric circulation, and thermospheric temperature on the structure and dynamics of the mesosphere and stratosphere?

(8) What factors affect the breakdowns of the polar winter circulation patterns in the stratosphere?

D. Coupling Among Radiation, Chemistry, and Dynamics

The structure of the upper atmosphere is the result of a rather intricate interplay among a large number of processes that, for simplicity, can be subdivided into the categories of radiation, chemistry, and dynamics (RCD). Any physical model of the upper atmospheric system attempts to incorporate at least parts of these components in a self-consistent fashion (see Fig. 11).

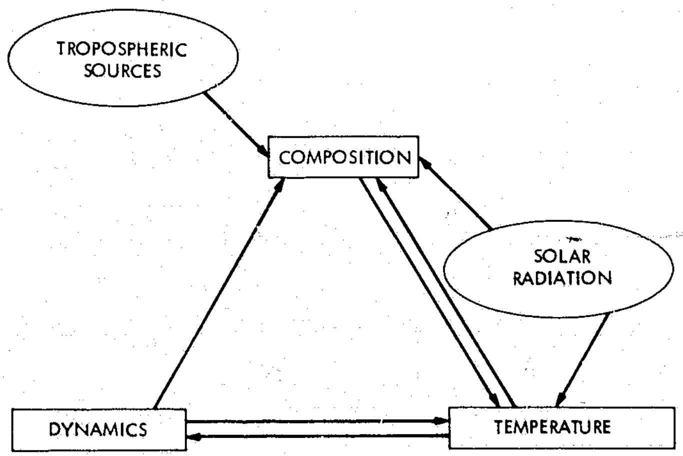

Fig. 11. Schematic representation of the relationships between radiation, dynamics, and chemistry

The development of a comprehensive RCD model of the atmosphere-cryosphere-ocean system is not anticipated in the foreseeable future. Nevertheless, a spectrum of models, extending from the simplified, which provide basic understanding and guidance, to the more comprehensive, will be necessary to develop a detailed understanding of the basic coupling processes. The process of model development cannot be complete until the models have been tested against observations, and the limits of their validity established.

1. Coupling among processes. Broadly speaking, the nature of the RCD interactions may be characterized by noting that modifications of chemical processes lead to changing concentrations of radiatively active gases, especially ozone, which, in turn, leads to changes in the motion field, modified transports, and further changes in trace gas concentrations. A particular example of such interactions is in the photochemical acceleration of radiative relaxation times (through the temperature dependence of reaction rates), which leads to increased damping of upward propagating waves.

To understand these coupling mechanisms in greater detail, it is instructive to focus on the interactions between radiation, dynamics, and chemistry, taken two at a time.

The basic large-scale circulation patterns of the atmosphere are the response to the strength and distribution, both geographic and seasonal, of the net radiative energy sources and sinks. In the troposphere, the major radiant energy source is at low altitudes at equatorial and tropical latitudes. The tropospheric radiant energy sink lies in the upper troposphere and extends to polar regions. This energy system drives a primary (Hadley) circulation that extends into and is responsible for a major part of the dynamics of the lower stratosphere.

In the upper stratosphere, net radiative heating at the summer polar stratopause, coupled with net radiative cooling in the winter polar upper stratosphere and mesosphere, is again responsible for a large scale thermally-direct circulation system, such that in the mesosphere there is a rising motion over the summer polar regions and subsidence over the winter polar region.

The vertical distribution of radiative heating and cooling also affects the dynamics by determining the static stability. Heating due to absorption of solar radiation by ozone gives rise to a region of high stability, the stratosphere, and a region of low stability, the mesosphere. Absorption of solar radiation by molecular oxygen and nitrogen gives rise to another region of high stability, the thermosphere.

In addition to driving motions in the upper atmosphere, radiative processes act to dissipate the energy of eddy motions by cooling to space. Thus, when motions create an increase in temperature, the increased infrared radiation emitted as a result of the temperature excess from equilibrium will tend to relax the temperature back to its equilibrium state. This process produces a radiative relaxation time scale that is as short as 5 days in the vicinity of the stratopause. This radiative relaxation time scale is quite comparable to a broad class of motions in the upper atmosphere.

A great number of trace constituents in the upper atmosphere have chemical time scales that are much greater than the time scales for transport. Examples are O_3 in the lower stratosphere and NO in the mesosphere. For these and other constituents, consideration of dynamics must accompany chemistry to correctly explain observed constituent concentrations. Perhaps the most striking examples of the importance of dynamics in this regard are the observed high concentrations of O_3 in the polar night stratosphere where photolytic processes are absent.

Although transport of chemical constituents takes place in response to motions on a variety of time and length scales, global distributions of species are primarily the results of chemistry and planetary scale motions with periods of several days and longer. Smaller scale motions are important in several contexts, however. The stratosphere-troposphere exchange of air is one of these. It has been estimated that 70 percent of the total stratospheric mass is exchanged with the troposphere each year. This occurs through several processes, but the dominant mechanism in the middle latitudes is thought to be frontal scale processes associated with the upper tropospheric jet stream. Radioactive tracers and studies of potential temperature and potential vorticity indicate that considerable amounts of stratospheric air are injected into the troposphere by these phenomena on spatial scales of 1 km in the vertical, 100 km in the horizontal orthogonal to the wind, and more than 1000 km parallel to the wind. Cumulonimbus convection has been commonly viewed as a means of upward transport of air from the troposphere, especially in the region of the intertropical convergence zone (ITCZ). It is not clear that this is an important mechanism, however, and recent observations indicate that very few clouds penetrate the high tropical tropopause. In fact, the data suggest that the reverse is true; i.e., stratospheric air is entrained and transported to the troposphere when cumulus cells collapse due to negative buoyancy and subsequently sink back into the tropospheric gases to the upper troposphere (100- to 250-mb region). This process may thereby play an indirect role in the exchange between these regions, since gases transported to the vicinity of the tropopause can then be carried to the stratosphere by the slow mean vertical motion associated with the stratospheric portion of the tropical Hadley circulation.

Transport also acts to change the temperature, and consequently photochemical rate coefficients, during such processes as stratospheric warmings. The transports of trace gases cannot be accurately calculated until such processes are included.

As has been mentioned previously, the distribution of ozone dominates the distribution of radiative heating in the stratosphere and mesosphere. Thus, a proper knowledge of the ozone photochemistry is required for understanding the heating distribution. Similarly, a good understanding of important processes in the distribution of H_2O and CO_2 is required to adequately explain the emission of atmospheric infrared radiation. Understanding the chemical reactions and processes leading to aerosol formation and destruction is also desirable since aerosols can potentially affect the earth radiation budget, especially after major volcanic eruptions.

2. **Coupling among atmospheric regions**. The origin of many of the atmospheric trace constituents lies at the surface of the earth. Biological and anthropogenic processes at the ground produce, among other constituents, CH_4, N_2O, CO, H_2, CH_3Cl, CF_2Cl_2, $CFCl_3$, and CCl_4. These gases have various loss mechanisms in the troposphere, but they all are transported to the stratosphere where destruction by ultraviolet radiation, $O(^1D)$ atoms, OH radicals and other processes provide a copious source of free-radical species. Processes that transport these constituents from the ground to the upper atmosphere thus provide an important link between the atmospheric regions. One example of troposphere-stratosphere chemical coupling of this type is the sulfur-aerosol-radiation complex discussed previously.

Chemical coupling processes are also active across the stratosphere-mesosphere, and mesosphere-lower thermosphere boundaries. For example, NO produced in the lower thermosphere and upper mesosphere by ionization processes is transported into the lower mesosphere where it is destroyed by photolysis followed by the reaction of N atoms with NO. In the polar winter, transport of this NO into the stratosphere may be possible. A further example is the production of atomic oxygen from O_2 by photodissociation in the summer lower thermosphere, which is then transported poleward to high winter latitudes and downward for recombination and the release of energy in the mesopause region.

By far the greatest amount of atmospheric energy resides in the troposphere. This energy can propagate upward as a wave energy flux by means of gravity waves, tides, and planetary-scale waves. This wave energy can be dissipated to heat at lower thermospheric altitudes by molecular viscosity and heat conduction. Some of this wave energy is dissipated still lower down as the energy produces dynamic instabilities that create turbulence. In addition, there are wave mean-flow interactions by which wave momentum is absorbed by the mean-flow. Thus, there exist many dynamic mechanisms by which the lower atmosphere can influence the upper atmosphere.

Meridional circulations driven in one region may couple dynamically into adjacent layers. An example of this is the possibility that the differential heating of the ozone layer gives rise to upward motion during the summer and downward motion during the winter at polar latitudes. This circulation pattern penetrates up to the mesopause region. The thermospheric circulation plays an important role in the global redistribution of energy, momentum, and changes in the neutral composition. Thus, as mentioned above, atomic oxygen is transported from the summer hemisphere to the winter hemisphere, and long-lived species produced in the aurora are transported to mid- and low-latitudes, where they diffuse downward to lower altitudes and affect the neutral composition and heating rates of the mesosphere and perhaps even the stratosphere.

Another type of coupling is that which may result from changes in the upper atmosphere that affect the transmissivity of wave energy upwards. This could lead to changes in the circulation at the level of the wave forcing. It has, for example, been suggested that solar disturbances heating the thermosphere might affect planetary wave transmission upwards, leading to changes in the tropospheric circulation. Recent theoretical calculations indicate that this mechanism is not a viable one. If, on the other hand, solar disturbances can affect ozone concentrations that changes the differential heating and thus the polar night jet intensity, such calculations indicate that tropospheric changes might be significant. In any event, if solar disturbances do affect the tropospheric weather, it very well might take place through some sort of dynamic coupling in the vertical. Also, man-induced changes in the upper atmosphere may induce changes in the dynamic coupling in the vertical that could affect tropospheric climate. Thus, it is crucial that future theoretical and observational studies of the coupled lower and upper atmospheric systems take place.

3. **Key scientific questions:**

(1) What are the relative contributions of the mean circulation, eddies, and planetary waves in determining trace constituent transport?

(2) How do feedbacks among radiation, chemistry, and dynamics serve to amplify or dampen upper atmospheric responses to perturbations?

(3) What is the nature of the chemistry-dynamics interaction that determines the identities and quantities of constituents "stored" during the polar night? How does the storage of slowly reacting species in the polar night affect global chemical budgets?

(4) What is the source of, and what determines the height, concentration and geographical variations of the aero-

sol layer(s)? What effects do aerosols have on the radiation budget?

(5) What is the global budget of the stratosphere-troposphere exchange?

(6) What is the spatial distribution of the major stratosphere-troposphere exchange processes?

(7) How are variations of trace gas concentrations and perturbations in the radiative budget of the middle atmosphere affected by breakdown of the polar winter/spring circulation systems?

(8) What is the influence of radiation damping on motions in the upper atmosphere?

V. Scientific Approach

A. Introduction

The scientific objectives of the UARS Program have been presented in the last section as a series of key scientific questions which relate to various complex processes and external influences acting within and upon the upper atmosphere. In most cases, answers to the scientific questions cannot be obtained through measurement of a single atmospheric variable, such as temperature, trace gas concentration or wind velocity. The questions posed are of such a nature that observations of a number of related variables are required, while the answers sought can be obtained only by placing the experimental data within the context of appropriate physical theory. A major objective in combining observations and theory in this way is the verification and validation of theory as related to the fundamental phenomena of the upper atmosphere.

B. Prioritized Science Objectives

The thirty-two key scientific questions given in the previous sections serve as the basic guideposts needed for the design of an effective satellite-oriented research program. The questions are diverse and reveal much of the current uncertainty about the relevant radiative, chemical, and dynamic properties of the upper atmosphere. To develop a rational program of research based upon these scientific objectives, it has been necessary to prioritize the questions in terms of their scientific importance. For those questions of highest urgency, a set of measurement requirements has been determined, giving the necessary atmospheric variables to be obtained and information about the required height resolution, spatial and temporal coverage, precision, and accuracy. With the measurement requirements established, surveys of existing and developing instruments have been undertaken to determine the extent to which the required measurements can be implemented.

In the present case, the SDG discussed extensively the set of thirty-two key scientific questions. Of these, twenty-seven were felt to be of sufficient immediate scientific importance for the SDG to recommend that they become the basis of the initial UARS Program. The key questions so selected are reproduced in Table 2, together with an indication of the relevant physical variables that must be measured satisfactorily to permit resolution of the particular question. Table 3 gives the list of less urgent questions, which may be appropriate for later evaluation as the UARS Program progresses.

It would be difficult to reproduce in this report the SDG's deliberations leading to the selection of questions placed in the highest priority category. The general opinion of the group was that this initial problem set should focus on the basic questions about atmospheric processes that relate directly to the development and validation of theory and theoretical models. As the program develops, topics receiving prime consideration are certain to change with the possibility that questions entirely omitted from the present list will receive their full share of attention at some later time.

From the list of questions given in Table 2, it can be seen that certain measured or derived quantities, such as temperature, winds, or ozone profiles, are common to a number of questions so that particular measurements can help to satisfy several scientific objectives simultaneously. However, in a number of cases the measurement requirements differ so that the needs of one particular objective will generally act as a driver to set the overall requirements on a particular variable.

Details of the measurements required by these scientific objectives are discussed below in Part II, Section 1.

C. Role of Data Analysis and Theory

The science objectives of the UARS Program, as outlined in initial form by the questions listed in Tables 2 and 3, involve a complex interplay of nonlinear radiative, chemical, and dynamic processes. It is a basic premise that no measurements program will ever be able to completely define the physical and chemical state of the upper atmosphere. Thus, theory, as expressed in numerical simulation models of varied complexity, must be relied upon to provide predictions about atmospheric phenomena that are not readily measured. Theory, however, is accurate only to the extent that the fundamental processes are adequately understood within the full range of upper atmospheric variability, including the effects associated with solar irradiation, magnetospheric processes, and lower atmospheric interactions. Therefore, the need to integrate observational data with appropriate theory is of paramount importance. Further, the measurements themselves must be of direct relevance to the scientific objectives of the program.

Table 2. Highest priority key scientific questions

1.	What is the solar radiation spectrum and its temporal variation between wavelengths of 120 and 400 nm?
2.	What is the global morphology of atmospheric radiative heating?
3.	What is the global morphology of radiative cooling?
4.	How accurately can theoretical radiative equilibrium models predict atmospheric temperatures below 70 km?
5.	What is the sensitivity of the stratospheric radiation budget to tropospheric parameters, such as cloud-top temperature?
6.	To what extent do energy sources associated with magnetospheric electric fields and particle precipitation affect the thermal balances of the lower thermosphere and upper mesosphere?
7.	What is the global distribution of ozone, and what are its temporal variations?
8.	What is the global distribution of the source molecules (e.g., N_2, CH_3Cl, CH_4, CF_2Cl_2, and $CFCl_2$) of the upper atmosphere radicals?
9.	What is the global distribution of molecules (e.g., HNO_3, HCl, H_2O_2, and N_2O_5) that serve as reservoirs (and/or sinks) for the upper atmospheric radicals (e.g., ClO_x, NO_x, and HO_x)?
10.	What is the global distribution of the radical families ClO_x, HO_x, and NO_x?
11.	What are the processes by which the sources and reservoirs determine the mean radical concentrations? How variable are these processes in time and space?
12.	What is the response of the upper atmospheric chemical system to external perturbations?
13.	What are the relative roles of energy generation in situ (by solar heating) and tropospheric energy fluxes in maintaining the upper atmospheric circulation?
14.	What is the strength and variability of the low-latitude Hadley cell? How are its energy and momentum balances maintained?
15.	Through what mechanism does the semiannual wind oscillation in the equatorial upper stratosphere occur?
16.	What mechanism is responsible for the warm winter and cold summer mesopause?
17.	At what altitude do ageostrophic wave motions dominate geostrophic motions?
18.	What role, if any, do in situ instabilities play in the upper atmosphere?
19.	What is the influence of the aurora, thermospheric circulation and thermospheric temperature on the structure and dynamics of the mesosphere and stratosphere?
20.	What factors affect the breakdowns of the polar winter circulation pattern in the stratosphere?
21.	What are the relative contributions of the mean circulation, eddies, and planetary waves in determining trace constituent transport?
22.	How do feedbacks among radiation, chemistry, and dynamics serve to amplify or dampen upper atmospheric responses to perturbations?
23.	What is the nature of the chemistry-dynamics interaction that determines the identities and quantities of constituents "stored" during the polar night? How does the storage of slowly reacting species in the polar night affect global chemical budgets?
24.	What is the global budget of the stratosphere-troposphere exchange?
25.	What is the spatial distribution of the major stratosphere-troposphere exchange processes?
26.	How are variations of trace gas concentrations and perturbations in the radiative budget of the middle atmosphere affected by breakdown of the polar winter/spring circulation systems?
27.	What is the influence of radiation damping on motions in the upper atmosphere?

Table 3. Lower priority key scientific questions

I.	What is the vertical attenuation of solar radiation in the wavelength range of 120 to 400 nm at altitudes between 10 and 120 km?
II.	What influence do discrete emission processes have upon the thermal balance of the mesosphere and lower thermosphere?
III.	What is the solar radiation spectrum and its temporal variation at X-ray wavelengths?
IV.	What are the diurnal variations of the radical and reservoir species and what is the impact on the average chemical budgets?
V.	What are the roles of heterogeneous and surface reactions in the chemical and ionic processes of the upper atmosphere?
VI.	What is the role of ion chemistry in determining the structure of the normal, quiet upper atmosphere, as well as the upper atmosphere during such perturbations as solar proton events, relativistic electron precipitation, and nuclear explosions?
VII.	What is the source of, and what determines the height, concentration and geographical variations of the aerosol layer(s)? What effects do aerosols have on the radiation budget?

To extract optimal scientific return from UARS observations, it is essential that the experimental data be distributed rapidly to all investigators, experimental and theoretical, in a format conducive to the performance of comparative and diagnostic studies. It is anticipated that the comparison of data with model predictions will be an important function of the theoretical groups, leading to improved knowledge of the full range of basic effects influencing the structure and behavior of the upper atmosphere. Diagnostic studies based upon data can be used with theoretical ideas to determine energy, momentum, and constituent balances. In both cases, theoretical models spanning a wide range of complexity will be required to understand the underlying physics and chemistry of the regions examined by the satellite experiments.

Data reduction, diagnostic studies, and numerical simulation studies all have their own computational requirements that must be satisfied within the UARS Program on a basis equivalent to that given individual experiments. As described in detail later, the UARS Program as developed here should include both experimental and theoretical teams headed by principal investigators. While a particular experimenter will undoubtedly have interests spanning a range of topics, his main concern will lie in the data produced through his own instrument. For remote sensing instruments, however, the reduction of radiance data to a physical parameter varying with altitude can be extremely complex, and it is expected that theoreticians involved with UARSP may play an important part in the deconvolution and interpretation of these data. Another style of theoretical effort is required for geophysical analysis to determine the physical processes acting within the atmospheric medium as deduced from the data interpreted as temperatures, concentrations, and winds. Both types of theoretical efforts are essential to the success of the program and serve to underline the need for an intrinsic balance between theoretical and experimental work in organizational structure and funding.

Part II. Program Requirements

I. Instruments

A. Measurement Requirements

To determine the instruments needed for the UARSP missions, a set of requirements has been generated for measurements necessary to answer the scientific questions listed in Table 2. Two sets of measurement requirements have been generated. One set gives the measurement accuracies, precisions, altitude range, altitude resolution, temporal resolution, spatial resolution, and coverage "desired" for obtaining the best result. A second set gives less stringent values for these same parameters "adequate" for obtaining a minimum useful result.

Table 4 provides a summary of the measurement requirements for the highest priority science questions listed in Table 2, while Table 5 provides a summary of the measurement requirements for science questions of lower initial priority (Table 3) for inclusion in subsequent missions in the UARS program. The measurement requirements of Table 4 apply to the most important quantities to be measured without regard to ease of measurement. For each science question requiring species measurements, Table 4 indicates which of these species must be measured (above the dashed line) to provide an adequate answer to the question posed, and which additional species (below the dashed line) would be desirable to measure as well.

B. Strawman Payloads

After defining the measurement requirements, a complement of instruments was chosen to fulfill these requirements. This complement of instruments, or "strawman payload", was derived by comparing a listing of instruments and instrument capabilities with the adopted measurement requirements. This procedure is outlined in greater detail in the Appendix. The list of instruments was obtained from a survey of remote sensing instruments presently being used on balloons and earth orbiting satellites, and from instruments presently under development for these same platforms. The instrument capabilities were obtained from a survey of principal investigators. The instrument list is not necessarily exhaustive, the instrument capabilities are not necessarily completely defined, and the derived strawman payloads are not necessarily unique. The actual payload will be chosen from responses to an Announcement of Opportunity. The purpose of the strawman payload is to derive spacecraft requirements and to demonstrate the feasibility of a remote sensing measurements program.

Two major requirements placed on the instruments by the SWG are:

(1) Complete vertical distribution in 85 s for most measurements.

(2) Vertical profiles to a resolution of $\Delta h \leqslant 3$ km for most measurements.

The first requirement has its origin in the desire to have an orbital inclination of 56 deg on the first mission, and corresponds to the 500-km zonal resolution set for most measurements. The second requirement is based upon the need to obtain vertical distribution of most quantities for theoretical analyses to a resolution better than one-half scale height. This resolution is difficult to achieve with down-looking instruments so that most of the instruments chosen to meet the measurement requirements given in Table 3 are limb scanning instruments.

Limb scanning instruments can be categorized as limb emission instruments or solar occultation instruments. Solar occultation measurements can be taken at only two points on the terminator during each orbit, whereas limb emission measure-

Table 4. Measurement requirement guidelines

	Measurement	Altitude range, km		Capability		Spatial resolution[a], km		Temporal resolution	
		Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired
1	Solar flux	Not applicable		(Δλ, nm/accuracy %/precision %)		Not applicable		Daily. More frequent for special solar events	Same
	Ly-α			1.0/10/5	1.0/5/3				
	175–195 nm			1.0/10/5	0.5/5/3				
	195–225			0.5/10/5	0.3/5/3				
	225–285			3/10/5	3.0/3/3				
	285–330			0.5/3/1	0.5/1/0.5				
	330–440			5.0/1/0.5	5.0/0.5/0.3				
	440–760			10/1/0.5	5.0/1/0.3				
2	Radiative heating								
	O_3	20 – 70	Tropopause – 100	10% accuracy/ 5% precision	5%/1%	3 × 1000 × average	3 × 500 × 2500	Global every 3 days plus complete global in one day once a month	Global coverage in one day, weekly
	Cloud cover			10% accuracy	1%				
	Cloud-top temperature			3 K accuracy/ 1 K precision	1 K/0.5 K				
3, 5	Radiative cooling								
	O_3	20 – 70	Tropopause – 100	20% accuracy	10%	3 × 1000 × average	3 × 500 × 500	As in 2 above except CO_2 mixing ratio should be measured in situ several times per year using associated rocket launchings	
	CO_2			10% accuracy	5%				
	H_2O			50% accuracy	20%				
	Temperature			3 K accuracy/ 1 K precision	1 K/0.5 K				
	Cloud cover				as in 2				
	Cloud-top temperature				as in 2				
6	Nonradiative heating								
	3914 Å emission			10% accuracy	5% accuracy	3 × 500 × 500 in the auroral zone		Emphasis on latitudes >40 deg Periodically at opportunities	
	Electric fields								
	Particle flux								
	Electrons 0.1–400 keV	in situ							
	Protons 0.5–30 MeV								
	Birkland Currents								
8, 11	Source molecules								
	CH_4	Tropopause – 50	from tropopause to as high as possible	20% accuracy/ 10% precision for budgets 10% accuracy for variability	5%/2% for budgets 2% accuracy for variability	3 × 500 × average for budgets 3 × 500 × 1000 for variability	1 × 500 × 500	Zonal (lat. ≤ 60 deg) monthly average for budgets. Global (lat. ≤ 60 deg) every few days over 2 weeks for variability	Global monthly average for budgets. Same for variability
	H_2O	Tropopause – 50							
	N_2O	Tropopause – 40							
	$CFCl_3$	Tropopause – 30							
	CF_2Cl_2	Tropopause – 40							
	CH_3Cl	Tropopause – 35							
	CH_3CCl_3	Tropopause – 40							
7, 9, 11	Reservoir molecules								
	O_3	20 – 50	Tropopause – 90	20% accuracy/ 10% precision for budgets 10% accuracy for variability	5% accuracy/ 5% precision for budgets 2% accuracy for variability	3 × 500 × average for budgets 3 × 500 × 1000 for variability	1 × 500 × 500	Zonal (lat. ≤ 80 deg) monthly average for budgets. Global (lat. ≤ 80 deg) every few days over 2 weeks for variability	Global every few days for budgets and variability
	HNO_3	20 – 30	Tropopause – 40						
	H_2O	Tropopause – 50	Tropopause – 90						
	HCl	20 – 50	Tropopause – 60						
	HF	20 – 50	Tropopause – 60						
	NO	60 – 100	60 – 100						
	CO	20 – 60	Tropopause – 100						
	H_2O_2	20 – 50	Tropopause – 60						
	N_2O_5	20 – 30	Tropopause – 40						
	$ClONO_2$	20 – 30	Tropopause – 40						
	H_2	40 – 90	40 – 150						

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Table 4 (cont)

	Measurement	Altitude range, km: Adequate	Altitude range, km: Desired	Capability: Adequate	Capability: Desired	Spatial resolution[a], km: Adequate	Spatial resolution[a], km: Desired	Temporal resolution: Adequate	Temporal resolution: Desired
10, 11	Radical species								
	O_3	20 – 60	Tropopause – 100	20% accuracy/ 10% precision for budgets 10% accuracy for variability	5% accuracy/ 5% precision for budgets 2% accuracy for variability	3 × 500 × average for budgets 3 × 500 × 1000 for variability	1 × 500 × 1000	Zonal (lat. ≤ 80 deg) monthly average for budgets. Global (lat. ≤ 80 deg) every few days over 2 weeks for variability	Global every few days for budgets and variability
	CO	20 – 60	Tropopause – 100						
	OH	25 – 40	20 – 80						
	ClO	25 – 40	20 – 50						
	NO_2	25 – 60	20 – 60						
	NO (strato)	25 – 60	20 – 60						
	NO (meso)	60 – 90	60 – 100						
	O	60 – 90	50 – 100						
	HO_2	25 – 40	20 – 80						
12	Response to Perturbations								
	H_2O			Same as variability requirements for "reservoir species"				Targets of opportunity	
	O_3								
	NO (meso)								
	CO								
	HCl								
	HF								
	ClO								
	OH								
	NO (strato)								
	O								
	HO_2								
	H_2O_2								
	$ClONO_2$								
	N								
13, 14, 16, 18, 19, 27	Extratropical dynamics								
	Temperature	Tropopause – 70	Tropopause – 120	1 K precision	1 K precision	3 × 500 × 1000	3 × 500 × 1000	Global (lat. 20 – 80 deg) daily	Global (20 deg-pole) daily
	Winds[b]	70 – 120	Tropopause – 120	10 m/s	5 m/s				
13, 14, 15, 17, 27	Tropical dynamics								
	Temperature	Tropopause – 60	Tropopause – 120	1 K precision	0.5 K precision	2 × 250 × 2500	1 × 250 × 2500	Global (lat. 0 – 20 deg) daily	Same
	Winds	Tropopause – 60	Tropopause – 120	2 m/s	1 m/s				
17	Geostrophic vs ageostrophic								
	Temperature	65 – 100	65 – 100	2 K precision	1 K precision	3 × 500 × 1000	3 × 500 × 1000	Global daily	Same
	Winds	65 – 100	65 – 100	10 m/s	5 m/s	5 × 1000 × 5000	3 × 500 × 1000	Global (20 deg–pole) daily	
18, 20, 27	Stratospheric warmings			Dynamics coverage same as "extratropical dynamics"; chemistry coverage same as "radiative cooling"					
19, 20	High latitude processes								
	O_3	60 – 90	50 – 100	25% accuracy/ 25% precision	10%/10%	3 × 500 × 500 in the auroral zone		Emphasis on lat 40 deg weekly	Global daily
	NO								
	OH								
	O								
	N (^4S)								
	N (^2D)								

Table 4 (cont)

	Measurement	Altitude range, km		Capability		Spatial resolution[a], km		Temporal resolution	
		Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired
21	Transport								
	O_3	Tropopause – 35							
	CH_4	35 – 60							
	H_2O	Tropopause – 50							
	N_2O	15 – 35							
	HNO_3	15 – 35							
	NO (meso)	60 – 100		Same as "reservoir species" for variability				Daily, continuous in winter	
	CO	Tropopause – 60							
	$CFCl_3$	Tropopause – 40							
	CF_2Cl_2	Tropopause – 40							
	HF	Tropopause – 40							
23	Polar storage								
	O_3								
	HNO_3								
	HCl								
	NO_2	20 – 50		Same as "reservoir species" for variability					
	H_2O_2								
	N_2O_5								
	$ClONO_2$								
	HOCl								

[a] Vertical resolution should be better than 1/2 scale height, taken as 3 km in this column.

[b] Wind measurements desirable, not required, for extratropical dynamics.

The adequate values shown for vertical resolution and altitude range are based on our present understanding of the atmosphere utilizing both theory and experimental measurements. For each source molecule, the adequate upper altitude was set to be that where the mixing ratio of the species is one order of magnitude less than that at the tropopause. Above this altitude, the source species play less of a major role in the budget than the radical and reservoir molecules in their respective families. However, important transport information can be gained from measuring these same species at higher altitudes. These upper altitudes serve only as a guide as the rate of removal of source molecules with altitude is latitude dependent. Therefore these values approximately represent a latitude of 30 deg. The adequate vertical resolution is shown to be 3 km, but again this should only serve as a guide depending upon the species to be monitored. For a species where the mixing ratio changes rapidly with altitude, i.e., small scale height, as in the case of $CFCl_3$ where the mixing ratio decreases by an order of magnitude between 15 and 28 km at 30 deg, and 15 and 24 km at 60 deg, the requirements placed upon the vertical resolution are more stringent than for a species where the mixing ratio is relatively constant with altitude, e.g., CH_4. Therefore any meaningful measurement must have a vertical resolution at least equal to the mixing scale height of the species being monitored.

The criteria used for choosing the adequate values for altitude range and vertical resolution for reservoir species and radical species are similar to those used for source species. The adequate altitude regime is that where the species significantly contributes towards their family budgets. Vertical resolution is again controlled by considerations of the mixing ratio profile, e.g., for a molecule like HNO_3 which shows a layered structure (15 – 38 km) vertical resolution of less than 3 km is required for both budget and transport calculations, whereas for molecules like HCl and HF the requirements are less stringent.

Table 5. Additional measurement requirements for following missions

	Measurement	Capability	Spatial resolution	Temporal resolution
I[a]	Vertical attenuation of solar flux	(Complementary in situ measurements using balloons and rockets)		
	Non-LTE cooling			
	CO_2, 15, 4.3, 2.7μ emissions	10%	above 20 km	Periodically
	NO, 2.8, 5.3μ emissions	10%	3 X 500 X 500	
	CO, 4.7μ emission	10%	higher in auroral zones	
	OH, 2–4μ emission	10%		
	NO^+, 5.2μ emission	10%		
	O_2 ('Δ), 1.27μ emission	10%		
	temperature	±10 K accuracy		
III	Solar X-ray flux			
	X-rays, broadband	5% accuracy/ 1% precision		Daily
IV	Dirunal variation	Same as "reservoir" and "radical" species in Table 3.		
VI	Ion chemistry			
	NO^+, 5.2μ emission		70–100 km vertical distribution	Variable opportunities
	NO, 5.3μ emission			
	N_2^+, 3914 Å emission			
	Particle flux			
V, 13, 17, 27	Tides and gravity waves			
	Temperature 30 – 120 km	1 K precision	5 X 500 X 1500	Every 6 h
	Wind 30 – 50 km	1 ms^{-1}		
	50 – 120 km	5 ms^{-1}		
VII	Aerosols			
	Aerosol distribution			
	SO_2	10%	1 X 500 X 500	In situ measurements of SO_2, NH_3, OCS to determine necessity for satellite measurement
	NH_3			
	OCS			

[a]Roman numerals are keys found in Table 3; arabic numerals are keys found in Table 2.

ments can be made at any time and at any geographic point on the limb. Given the orbital conditions being considered for the first mission in the UARS program, global coverage can be obtained in 1 to 3 days with limb emission instruments, and 20 to 30 days with limb occultation instruments.

Limb scanning instruments can also be categorized as radiometers or as spectrometers. Spectrometers are survey instruments capable of obtaining data on a large number of species simultaneously, but require very high data rates. Radiometers are specific to one or a small number of species, and are smaller, lighter, less complex, and operate at much lower data rates than do spectrometers. Limb scanning instruments also have various requirements for cooling, including cryogenic cooling.

In matching instruments to meet the measurement requirements, two approaches have been taken to bound the requirements on the satellite. In the first approach, species-specific instruments are used as candidates. This approach results in minimum demands on the spacecraft and results in unique necessities for instrument development. The second approach involves using a survey-type spectrometer as a core instrument capable of measuring the maximum number of quantities possible with the required coverage. To support the survey spectrometer, several species-specific instruments are necessary. This second approach imposes maximum requirements on the spacecraft weight and data handling. The dual approach adopted here yields an indication of payload extremes, and gives a range of parameters against which the satellite requirements can be estimated to prevent potential exclusion of any particular instrument from the payload during the lifetime of UARSP.

The quantities that can be readily measured using existing species-specific emission instruments include solar flux, temperature, stratospheric winds, cloud cover, cloud-top temperature, O_3, H_2O, CH_4, N_2O, CO, HNO_3, NO and NO_2. Table 6 gives Payload A, which contains the species-specific instruments (listed in Table A-1 of the Appendix) most suitable for measurement of these species in emission. These instruments form a "core" of instrumentation that must be augmented to measure species that are more difficult to measure in emission than the above.

The remaining measurement requirements are met by choosing instruments from on-going instrument development efforts. New instruments presently under development that appear to have a potential value for meeting the necessary

Table 6. Payload A (based on species-specific instruments)

Instrument/measurement	Weight, kg	Orbital average power, W	Orbital average data, kb/s	
UV spectrometer Solar flux[a]	16	12	0.03 (3.2[b])	
Doppler interferometer Winds (strato)	19	20	1.6	
Modulated gas cell radiometer T (meso), CH_4, N_2O, H_2O, CO, NO (strato) [T (strato)]	35	24	0.5	
Filter radiometer T (strato), NO_2, HNO_3, O_3 (strato) [N_2O, CH_4, H_2O]	161	40	6.0	
Nadir emission radiometer Cloud cover, cloud-top temperature	9	9	2.0	
Emission radiometer NO (meso)	85	40	1.0	
Occultation radiometer (HCl, HF, CF_2Cl_2]	75	40	0.4 (4.0[c])	
UV airglow emission spectrometer 391.4-nm emission	6	2	0.5	Instruments available
1.27μ emission spectrometer [O_3 (meso)]	6	2	0.06	↑
Far IR spectrometer OH, HCl, $CFCl_3$, CF_2Cl_2, CH_3Cl, HO_2, HF, $ClONO_2$, H_2O_2, N_2O_5, $O(^3P)$	520	40	15.0	↓ New developments
Laser heterodyne radiometer [ClO, $CFCl_3$, CH_3Cl, $ClONO_2$, HO_2]	143	150	0.4 (4.0[c])	
Microwave limb sounder Winds (meso), O_3 (meso), ClO [T (meso), H_2O_2]	300	300	3.0	
Totals	1375	679	30.49	

[a]Primary measurements for each instrument are indicated immediately below the instrument name. A bracketed entry under the instrument name indicates species that could be measured by the instrument either for redundancy or as back-up measurements where instrument developments may not be forthcoming. The species listed do not necessarily bound the full capability of each instrument.

[b]Peak data rate for 10 min/day.

[c]Peak data rate for <600 s/orbit.

requirements are listed below the dashed line in Table 6. Occultation radiometers are also included in Payload A where the occultation method is adequate, or for back-up capability if emission instruments do not become available. As is the case for all of the instruments listed in the strawman payloads, the instruments listed in Table 6 are included only as typical examples and do not preclude other potential instruments or instrument developments.

The details of the selection leading to the instruments of Table 6 and associated implications for instrument development are presented in the Appendix. There exists certain difficult measurements for which emission instruments are presently not available. These measurements are listed below, together with an indication of the importance of the measurement to the program and comments about the type of instrument that may be required.

HCl

An occultation radiometer is sufficient for obtaining global coverage once a month, but is insufficient for understanding the variability or the response to perturbations, such as volcanos. An emission instrument is desirable but presently unavailable.

HF

An occultation instrument would be sufficient. HF is a good tracer for transport studies, and could be used as such when and if the capability to measure HF in emission exists. Otherwise, an acceptable experiment on transport could be conducted without measuring HF.

CF_2Cl_2, $CFCl_3$, CH_3Cl, CH_3CCl_3

The spatial and temporal coverage obtained using an occultation instrument is acceptable. Development of an instrument specifically to measure these individual species in emission does not appear particularly difficult, and would probably result in considerable savings in weight and data transmission requirements over the use of a spectrometer.

H_2O_2, N_2O_5, $ClONO_2$

An in situ measurement of the concentration of these species is recommended to evaluate their potential roles as reservoir species and to assess the necessity of measuring them on a free-flying satellite. An emission instrument would be desired.

OH, ClO

These are extremely important radical species. Early development of instruments to measure these species is required. OH measurement in emission is required. ClO probably has a significant diurnal variation so that an emission instrument would also be desirable for this species.

O (mesosphere)

No instrument presently available. The two emission lines available are 63 μm and 147 μm.

O_3 (mesosphere)

Presently available limb emission instruments for O_3 are limited to measurement below about 65 km. Measurement of O_3 to at least 90 km on a weekly basis is required for understanding high-latitude processes. An emission instrument is required.

Winds (mesosphere)

Wind measurements to 100 km are required to determine the accuracy of using the geostrophic approximation in deriving winds from the temperature field and to examine extratropical dynamics in general. Also, direct wind measurements will be required in the equatorial region due to breakdown of geostrophy. An emission instrument is required to meet the daily global coverage requirement.

To summarize, the quantities in the "more difficult" list that are deemed most important to measure are HCl, OH, $O(^3P)$, O_3 (meso) and winds (meso) in emission, and HF, CF_2Cl_2, $CFCl_3$, CH_3Cl, CH_3CCl_3 and ClO in either occultation or emission, with emission being more desirable, especially for ClO. The importance of measuring H_2O_2, N_2O_5 and $ClONO_2$ from a satellite is unresolved, and these species may be measured on later missions if not on the first. Measurements of HO_2, HOCl, $N(^4S)$, $N(^2D)$, $O(^1D)$ and the sulphur species are not deemed necessary to conduct acceptable chemistry and transport experiments, but their measurement would be desirable, if possible.

Table 7 gives a second payload, Payload B, which results from a selection strategy different from that used to arrive at Payload A. Payload B uses a cryogenic limb emission spectrometer as a core instrument. This latter instrument is presently under development and not yet available, but does meet the measurement requirements for a large number of the quantities given in Table 4. However, the cryogenic cooling system required for the instrument imposes a duty cycle limitation, which present projections indicate is on the order of 15% for an 18-month mission lifetime. The temporal and spatial coverage that can be obtained is therefore limited. This restriction implies that emission radiometers are probably best used for measurements of species that require high spatial and

Table 7. Payload B (emission spectrometer based)

Instrument/measurement	Weight, kg	Power, W	Data, kb/s	
UV spectrometer Solar flux[a]	16	12	0.03 (3.2[a])	
Doppler interferometer Winds (strato)	19	20	1.6	
Filter radiometer O_3 (strato), T (strato)	161	40	6.0	
Modulated gas cell radiometer T (meso), H_2O	35	24	0.5	
Nadir radiometer Cloud cover, cloud-top temperature	9	9	2.0	
Occultation radiometer [HCl, HF, CF_2Cl_2]	75	45	0.4 (4.0[b])	
UV airglow spectrometer 391.4 Å airglow	6	2	0.5	Instruments available ↑
Cryogenic limb interferometer spectrometer CO, HNO_3, NO (strato), NO (meso) NO_2, CF_2Cl_2, $CFCl_3$, ClO, CH_4, N_2O [T, O_3, H_2O]	570	150	20.0	↓ New developments
Far IR spectrometer OH, CH_3Cl, HCl, HF, $ClONO_2$, H_2O_2, N_2O_5, $O(^3P)$	520	40	15.0	
Microwave limb sounder Winds (meso), O_3 (meso)	300	300	3.0	
Totals	1711	642	49.03	

[a]Primary measurements for each instrument are indicated immediately below the instrument name. A bracketed entry under the instrument name indicates species that could be measured by the instrument either for redundancy or as back-up measurements where instrument developments may not be forthcoming. The species listed do not necessarily bound the full capability of each instrument.

[b]Peak data rate for 10 min/day.

[c]Peak data rate for <600 s/orbit.

temporal resolution, such as O_3, H_2O and temperature. Instruments are also required to support the cryogenic spectrometer for measurement of HCl, HF, $CHCl_3$, CH_3CCl_3, H_2O_2, N_2O_5, $ClONO_2$, OH, 3914 Å airglow, cloud parameters, winds, and the solar flux. As a result, Payload B is the same as Payload A with addition of the cryogenic interferometer and deletion of the laser heterodyne instrument, the NO emission radiometer, and the 1.27-μm radiometer.

Given the present state of the instruments, Payloads A and B come up short for making the required measurements of HCl, OH and $O(^3P)$ in emission, $CFCl_3$, CH_3Cl, CH_3CCl_3, and ClO in either emission or occultation, and measurement of mesospheric winds. If instruments are not available for these species by the time UARS flies, and the necessity for their measurement is firmly established, then alternate mission strategies could be developed. For example, some of the above species might be measured by a Spacelab mission dedicated to measurements in concert with UARS, or an occultation spectrometer might be included on UARS. The large spectrometers carried on Spacelab, and both the solar occultation and cryogenic emission interferometers could be used to provide supporting measurements in the short term for UARS by measuring species that the small species-specific instruments on UARS cannot easily measure themselves. In this way it may not be necessary to fly the larger, more complex spectrometer instruments on UARS.

Table 8 lists additional instruments matched to the requirements in Table 4 for measurement on UARS missions subsequent to the first. The electric field, particle flux and magnetic field measurements would be flown on polar missions. The IR

Table 8. Additional instruments for subsequent missions

Instrument/measurement	Weight, kg	Power, W	Data, kb/s
IR airglow spectrometer $1.27\mu(O_2\,^1\Delta)$, $2\text{–}4\mu$ (OH), 2.7μ (CO_2), 2.8μ (NO), 4.3μ (CO_2), 4.7μ (CO), 5.2μ (NO^+), 5.3μ (NO), 15μ (CO_2)	10.0	10.0	2.0
Electric field	4.5	5.0	1.0
Particle flux Electrons, 0.1–400 keV Protons, 0.5–30 MeV	6.9	5.5	1.0
Magnetic field	2.7	4.0	0.3
Total	24.1	24.5	4.3

airglow instrument would be used to address questions concerning non-LTR processes and ion chemistry.

C. Instrument Developments

From the preceding discussion, instruments for the measurement of the following quantities in emission are required: HCl, OH, $O(^3P)$ O_3 (mesosphere), and winds (mesosphere). New instruments are required for $CFCl_3$, CH_3Cl, CH_3CCl_3 and ClO). Species-specific emission instruments are preferred for the latter, and would also be desirable for measurement of HF and CF_2Cl_2 as well.

Wind measurement is another area where specific instrument development is required. While there is an instrument being built for measurement of stratospheric winds on Dynamics Explorer, no actual measurement has yet been made, and a number of different approaches might be contemplated. Methods for measurement of mesospheric wind fields also need to be developed, microwave limb sounding being one example.

Although not required for a first UARS mission, remote sensing techniques need to be identified for species such as $O(^1D)$, $N(^4S)$, and $N(^2D)$. Should it prove necessary to measure $ClONO_2$, N_2O_5, H_2O_2, or HO_2 from a satellite, methods for their remote measurement also will be required.

Present emission instruments do not have sufficient sensitivity for measurement of NO or NO_2 to the desired altitudes. Improved sensitivity might be obtained by additional cooling. Cryogenic cooling of instruments to maximize sensitivity consistent with the long-term nature of an individual UARSP mission is an area in which some resources would be well directed. Cryogenic cooling of instruments is critical in some cases to attain required sensitivities.

Present instruments and inversion techniques for deriving accurate (±1 K) temperatures from CO_2 limb radiance is another area in which refinement would be desirable. Related to the latter is a need to examine inversion routine requirements and ensure accurate laboratory data on molecular absorptions.

II. Spacecraft

The projected retrieval and reuse, or possible in-orbit refurbishment, of the UARS impose the requirement that the basic design of the spacecraft be capable of accommodating the highest mass, power, etc., anticipated for the instrument payload throughout the program. This also implies that the various spacecraft should be identical in all respects relating to instrument mechanical and electrical interfaces.

A. Instrument Accommodation

The strawman instrument complement for the first mission is shown in Tables 6 and 7 above. The spacecraft design must be able to accommodate the mass and power for this set of instruments, and form the platform capable of mounting the sensors with their required look angles and free fields of view. In addition, however, the spacecraft design should anticipate the follow-on missions when other sensors will be included, and have provision for accommodating them as well. The instrument with the largest mass and volume impact on the spacecraft foreseen in future missions is the cryogenic limb interferometer (see Table 7); when this instrument is included, one can anticipate not needing certain other instruments (e.g., the laser heterodyne radiometer). In this case, the weight requirement goes up while the power required decreases. Thus, the spacecraft should accommodate an instrument mass of about 2000 kg and provide for an instrument power requirement of about 1000 watts.

B. Shuttle Retrieval and/or Refurbishment

Scientific considerations call for data acquisition over longer times (e.g., the eleven-year solar cycle) than are foreseen for instrument cryogenic lifetimes and for high absolute measurement accuracies. The latter will probably require confirmations and/or updating of instrument calibrations or replacement of entire instruments. In addition, it will be extremely desirable to maintain a full instrument complement, even anticipating the possibility of failure of one or more instruments. These considerations dictate the use of the Space Transportation System (STS) for retrieval and/or in-orbit refurbishment of the UARS. Thus the basic spacecraft, as well as the instruments, should be designed to facilitate this portion of the mission operations.

C. Propulsion

The orbit proposed for the UARS is circular in the range of 400 to 600 km (Section IV, this Part), while, on the other hand, the parking orbit projected for the Shuttle is about 300 km. Thus there is a need for an on-board propulsion system to raise the orbital altitude of the UARS from the parking altitude to the desired operational altitude, and, when the mission is terminated, to lower the orbital altitude for retrieval or refurbishment by the Shuttle. The propulsion system should also provide for altitude restoration if atmospheric drag significantly reduces the orbital altitude during the mission lifetime.

D. Attitude

The attitude knowledge and control requirements are set primarily by the wind sensors and limb scanning radiometers that sense temperature and trace species. The requirement on the spacecraft is to provide attitude pointing accuracy of 0.01 degree and knowledge of the attitude to 0.003 degree, with a rate equal to or less than 2×10^{-5} degrees per second.

E. Telemetry and Data Handling

Use of the Tracking and Data Relay Satellite System (TDRSS) will be required in the time frame of the UARS. Thus the spacecraft must be compatible with the TDRSS, incorporating the appropriate antennae and transmitters. An on-board tape recorder will be required due to the incomplete spatial coverage offered by the TDRSS.

Any special on-board data processing (e.g., fast Fourier transforms) will be the responsibility of the Principal Investigator for the specific instrument and will not be supplied by the spacecraft.

III. Data System

The value of a central, dedicated data handling and computing system to the overall scientific success of a research oriented satellite program has been well demonstrated by the Atmospheric Explorer project. The ability to rapidly acquire, process, and disseminate data, and at the same time to carry out parallel theoretical computations, serves to encourage a high level of scientific participation by Principal Investigators and selected guest investigators. Further, the capability for storing project data in a central location readily accessible from remote sites directly linked to the central facility encourages frequent scientific browsing and data analysis that is excessively cumbersome when done with individually transported magnetic tapes or other data storage media.

The SWG strongly endorses the establishment of a central data handling and computing facility for UARSP. From discussions within the group, it appears that the data handling requirements for UARS missions will be more extensive than was the case for the Atmospheric Explorer or the forthcoming Pioneer Venus mission. The intrinsic complexity of limb scanning remote sensing measurements, with their need for inversion to geophysical quantities, creates new demands upon the methods of data storage and presentation. Further, extensive theoretical analyses will be conducted with the data, and there will be a need for performing interactive experiments with singular events such as volcanic eruptions, magnetic storms, solar flares, or even widespread forest fires. All of these expectations lead to a number of separate requirements upon the overall configuration and operation of the UARSP data system. These requirements are described below.

1. From instrument studies conducted by the Goddard Space Flight Center and the Jet Propulsion Laboratory, it appears that UARS will be designed to use the multiple access mode of the Tracking and Data Relay Satellite. This leads to a data input of 4×10^9 bits/day to the UARS computing facility. During periods of simultaneous operation, a higher average rate will occur. Likewise, later missions may include instruments with higher data rates than presently included; e.g., imagers or very high resolution devices.

The UARS data system must be designed to accept the present data rates while remaining sufficiently flexible for future expansion.

Storage time for the raw experiment data should be no less than ten (10) days.

2. All of the raw data received from the satellites should be reduced to geophysical unit data (i.e., concentrations, temperature, solar flux, etc.), and stored with appropriate temporal and spatial locating information in a central facility. For routine operations, this reduction should require no more than

three days. Intermediate data sets (e.g., "calibrated" data such as radiances) should be stored on-line for 30 days. Geophysical units (G.U.) data should be stored on-line for a minimum of 18 months following acquisition.

3. The data reduction for many of the instruments will require the extensive use of fast Fourier transforms. The central facility should have the capability of performing these in an efficient and routine fashion.

4. Where appropriate, the geophysical unit data should be summarized, abstracted, or otherwise reduced in volume in an interpolated or smoothed manner agreed upon by the Science Team, and associated with common temporal and spatial references.

5. Certain derived quantities (e.g., total ozone, winds derived from temperature field) should be calculated on a routine basis and stored in the central facility for common reference.

6. Data from all instruments should be made available rapidly and routinely to all members of the Team for analysis and interpretation. This leads to the requirement of a centralized data base containing these data in easily accessible form. This requirement also implies the necessity of appropriate safeguards for the data in the central facility so that data from a particular instrument can be modified by only the responsible investigator.

7. Team members must have suitable interactive equipment to permit access to the central facility, to manipulate and work with any of the data sets, and to display the output in forms suitable for their requirements.

8. It is likely that data from sources other than UARS should be kept in the central facility. These would include data from other satellites (e.g., AMPS and OPEN), or coordinated experiments with ground or balloon platforms.

9. The central facility should contain a collection of atmospheric models (e.g., one dimensional photochemical and simple dynamic) suitable for interpretation and comparison of UARS data. These may include analytical empirical models of UARS data. The models should relate as closely as possible to the larger Global Circulation Models (or photochemical equivalents), which require much larger computers than the dedicated UARS facility.

10. Quick-look summary plots (e.g., microfilm) of selected abstracted data should be available to team members to assist them in selecting and assessing geophysically interesting phenomena for early analysis.

11. The facility should provide the mechanism for rapid and effective communication between members of the investigator team to assist them in the analysis and interpretation of the UARS data.

12. The data processing facility should be designed and implemented in a manner to facilitate the investigator's responsibility for reduction of the data to geophysical units, thereby allowing the investigators to expend more effort in the analysis and interpretation of the collected data. The data reduction programs should be developed prior to launch and, within a reasonably short time after instrument turn-on and check-out in flight, be suitable for batch processing at the central facility without the necessity of investigator interaction.

13. The system should have the capability of rapid data reduction for special event operations. Examples are magnetic storm sudden commencements, volcanic eruptions, and sudden warmings. In these situations, it will be necessary to assess data quickly to evaluate the need for possible changes in satellite operational configuration, including variations in spatial and/or temporal coverage. A quick-look capability requires that data be available in times on the order of one orbit. The special event requirement affects the design of the operational satellite control system, and emphasizes the need for efficient and interactive data communication links between team members. The special event will also be needed during initial instrument turn-on, check-out, and verification periods, and during coordinated measurements with balloons, rockets, AMPS, and so forth.

14. The time response required for standard data reduction, quick-look, and special event operations, and rapid communication among the investigators and the central facility points to the need for direct data links between the central facility and the remote sites. There should be no need to transport computer tapes or other data storage media, including receipt of raw data at the central facility.

15. Where appropriate, the remote facilities should have a capability for interacting with other, non-UARS-dedicated computers for specific research purposes. Examples of this are local computers already set up for individual instrument data reduction or analysis and large computers running sophisticated atmospheric models. It is anticipated that large programs such as these models or inversions necessary for data reduction would be run by the user on a machine other than the dedicated UARS computer, with the results fed back into the UARS computer.

Figure 12 illustrates in block diagram form the various elements of the distributed data handling and computational

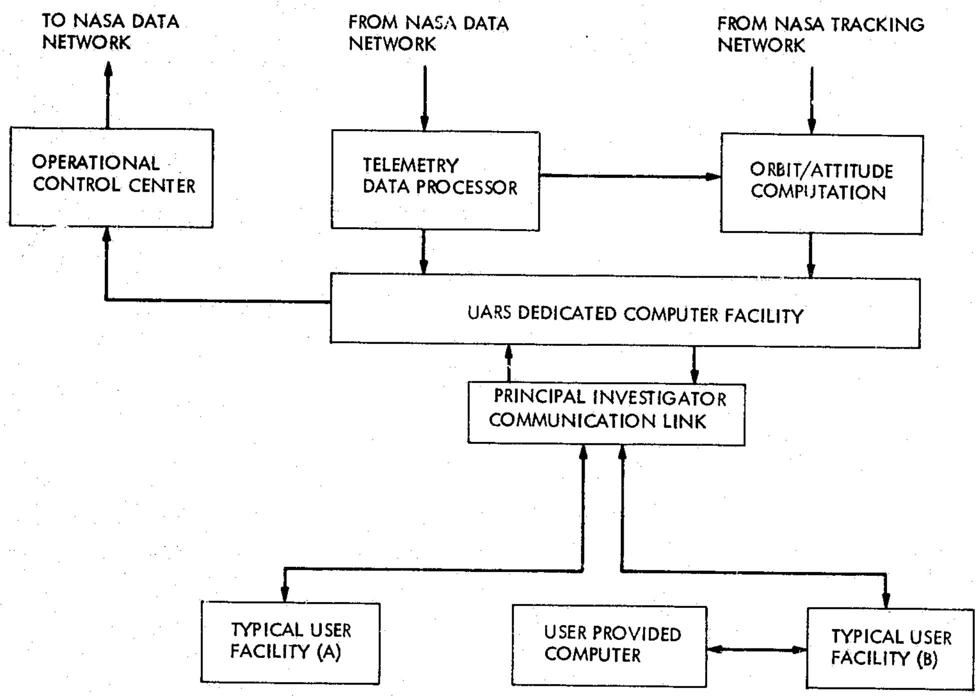

Fig. 12. UARS distributed data handling system

system recommended by the SWG. Communications between the Principal Investigators and the central facility are maintained through a dedicated link, telephonic or otherwise. Guest Investigators would be accommodated in a similar manner, subject to the availability of entry ports and constraints on system usage set by the Science Team.

In Figure 13, further detail of a typical remote user's facility is given. The use of a minicomputer to govern local data acquisition from the central facility plus local data processing and display appears essential. In addition, the minicomputer would provide access to additional computer resources that might be required. Such access could include a direct link to a local computer or a modem with dial-up capability to some other facility. It is anticipated, for example, that some theoretical investigators would need access to very large computers in the course of their studies. The system shown in Figure 12 would also ensure a rapid means of communicating the results of theoretical studies between team members.

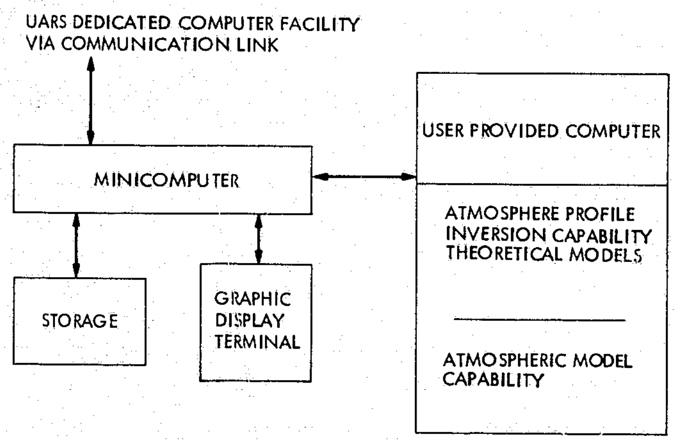

Fig. 13. Typical remote user facility

IV. Theory and Analysis

Theory and scientific analysis are essential ingredients of the UARS Program. As illustrated by the discussion in Section I, Part II, considerable care has been taken to ensure that the recommended measurements program satisfies the specific scientific goals set forth in Section III, Part I. Planning for a balanced scientific program must extend further, however, to include discussion of the way data obtained from measurements is used. The SWG firmly endorses the need for interpretation of the experimental results in terms of the basic physical and chemical processes acting within the upper atmosphere.

It is expected that the analysis objectives of the program will proceed with at least three phases. Initially, there will be an exploration phase where geophysical data are examined from a morphological point of view with emphasis upon the global and temporal distribution of various quantities such as trace constituent concentrations, temperatures, and winds. Following this, it is anticipated that analysis will develop in terms of simple scientific explanations with qualitative models based upon basic theory. In this phase, the morphological data will have special importance to diagnostic studies of energy and momentum budgets, providing information about basic physical processes. Finally, and building upon developments extracted in the first two phases, a quantitative comparison phase will develop where complex theoretical models are used to simulate atmospheric behavior and extensive comparisons are made between observation and prediction. A primary objective of these comparative studies will be the extension and validation of the appropriate atmospheric models with the intent of developing a capability for explaining the normal behavior of the atmosphere as well as the effects of perturbations.

Other theoretical activity can also be expected with regard to the interpretation of measured quantities in terms of geophysical parameters. This activity will normally occur within a given experiment team, but other individuals may become involved, especially with regard to interpretation of limb radiance data.

The need to provide a balanced program of diagnostic studies, qualitative model analysis, and quantitative comparison requires the participation of theoretical groups and adequate funding on an equitable basis with experimental work. Funding commitments for three or more years will be needed to develop and maintain the level of effort and participation required for a high level of interaction with the overall Science Team. Emphasis should be placed upon the need for the theoretical groups to include a project leader and supporting staff, including postdoctoral fellows or equivalent, and graduate students. At the institutional level, it is necessary to provide for a critical mass of intellectual activity related to the UARSP scientific problems, which should be the primary research activity of the group.

In addition to adequate financial support for each theoretical group, care must be taken to provide necessary remote computing facilities to assist the group in working with UARS data. A minicomputer, coupled with appropriate local graphics, hard-copy devices, and links to other computers will be required, along with technical personnel to maintain and develop the necessary system software and operational programs.

The theoretical groups should be chosen for participation in UARSP through the general Announcement of Opportunity issued for the overall program. A number of teams, perhaps four or five, should be selected on the basis of competence and their relationship to the broad areas of knowledge required by the program. Individual theoreticians should also be considered, but cannot be expected to contribute as effectively as teams.

Once selected, theoretical teams should participate immediately in the overall prelaunch program. This activity could include preliminary diagnostic studies aimed at supporting instrument planning, preparation for the basic UARSP models to be kept in the central computer facility, and the development of models needed for simulation studies.

As time passes, there will be a need for bringing scientists initially outside the program into contact with the scientific activities of the program. For some, designation as a guest investigator with funding and access to the computer facility may be appropriate. For others, access to data through experimental or theoretical Principal Investigators may be adequate. Annual workshops, similar to those that developed around Skylab data, should also be considered as a way of broadening scientific participation.

V. Orbit Considerations

An analysis of orbital parameters and viewing modes of several classes of satellite experiments has been conducted to define the characteristics of UARS missions that will satisfy the spatial and temporal coverage requirements for the desired atmospheric measurements. The launch site used for the mission will constrain the initial orbital conditions that can be obtained. Orbit inclinations for Shuttle launches from the Eastern Test Range (ETR) are a minimum of 28.5 deg and a maximum of 56 deg. Higher inclinations are obtainable through plane change maneuvers, but propulsion requirements are prohibitive for inclination changes of more than a few degrees. The most probable launch site for the first mission (planned for 1983) is the ETR since the WTR is not expected to be developed for Shuttle launch at that time. The maximum standard orbit inclination and altitude that can be achieved by the Shuttle from ETR is 56 deg and 300 km, respectively. For higher inclinations and altitudes, a propulsion system on the satellite is required. Orbit circulation is considered desirable to insure uniform geometry for measurements, and thus to facilitate data reduction and interpretation.

Four criteria emerge as the primary considerations in terms of orbital selection for UARS missions; they are listed in descending order of importance.

1. **Instrument size.** The greater the distance from an instrument to the sample being detected, the larger the optics

required of such an instrument to maintain spatial resolution and sensitivity. Since the distance to the limb of the earth, at a given sample height, increases approximately with the square root of the altitude of the spacecraft, the lowest possible altitude commensurate with the needed mission lifetime is desired.

2. **Geographical coverage.** Global coverage of the earth is possible by using various combinations of orbit inclination, altitude, and sensor technique. At a given inclination, the global coverage can be optimized by selecting as high an altitude as possible so that the limb be as remote as possible from the latitude constraints of the orbital plane itself.

3. **Atmospheric drag.** Even at an altitude of several hundred kilometers, atmospheric drag can have a significant degrading effect on the orbital altitude of a satellite. If a satellite is required to be maintained at a given altitude for a period of the order of years, as projected for UARS missions, orbital maneuvers must be carried out, at intervals, to counteract the effect of atmospheric drag. To reduce the potential problems associated with a high drag environment, the minimum satellite altitude should be ≥500 km.

4. **Orbital precession rates.** Within the relatively narrow band of altitudes to be considered for UARS missions (400 to 650 km), the orbital precession rates, in an inertial frame, vary only a small amount as compared to the significant variation of precession rate with orbital inclination. However, coverage patterns on the Earth's surface are sensitive to small variations in altitude, which suggests the suitability of specific altitude – inclination combinations to achieve the desired spatial resolution.

Since a primary criterion has not been identified, it is suggested that a range of altitudes from 400 km to 650 km is appropriate for (at least) the first two missions. An altitude of 600 km is used here for discussion of the effects of orbital inclination. Only marginal differences exist if altitudes around 400 km are selected. Besides providing nearly global coverage, the 600-km orbit will also precess through all local hours in approximately 36 days for temporal studies. The 600-km altitude is high enough to avoid excess atmospheric drag that would have to be overcome at lower altitudes by numerous, large propulsive maneuvers. Upon completion of a 1-year mission at 600 km, the satellite can return to 300 km and be retrieved by the Shuttle for repair, replacement, or calibration of the experiments.

The particular spatial and temporal resolution obtainable during a mission depends on the sensor technique employed. Figure 14 illustrates the latitudinal coverage capability for 600-km altitude solar occultation missions for orbit inclinations of 28.5 deg, 56 deg, 70 deg, and 98 deg (Sun synchronous). This figure also shows the seasonal limitations on geographical coverage for solar occultation missions.

Figure 15 shows the latitude coverage for a solar occultation experiment (e.g., spectrometer or radiometer) in making profile measurements of atmospheric constituents during spacecraft sunrise and sunset. These results are for a 1-year mission with a 600-km altitude, 56-deg inclination spacecraft orbit. The range of latitudes covered extends from 80°N to 47°S in the spring and summer, and from 47°N to 80°S in the fall and winter. The average time required to cover these latitude ranges is about 2½ weeks.

The distribution of solar occultation measurements as a function of both tangent latitude and longitude during a month (e.g., March) is illustrated in Fig. 16. During a day, a given latitude band is generally covered uniformly in longitude (~24-deg separation) at the sunrise or sunset conditions. Coverage at sunrise advances from the northern to the southern hemisphere, while coverage at sunset moves from the southern to the northern hemisphere with time. In the particular month shown, coverage extends from 80°S to 50°N with some overlap between the sunrise and sunset measurements. The distance between the measurements varies from about 2500 km near the equator to less than 500 km at the upper latitudes.

Although the solar occultation approach provides very high vertical resolution (2 to 3 km) for tenuous species, a greater number of measurements with higher spatial resolution can be obtained with limb emission techniques (e.g., a radiometer or spectrometer). For example, a limb scanner with a fixed azimuth angle of 0 deg provides geographical coverage capability as shown in Fig. 17. The coverage tracks of Fig. 17 are basically the same as ground tracks for this orbit. The three-day ground track repeat cycle results in a horizontal resolution of about 800 km at the equator, and further improves to only a few hundred kilometers at the mid- and upper latitudes. The progression of the orbital tracks during a typical three-day period is illustrated in Fig. 17. Figure 18 presents the geographical distribution of measurements for a fixed 90-deg azimuth angle over a one-day period. Spatial resolution increases toward higher latitudes. For higher spatial resolution at all latitudes, a limb emission radiometer sensor with a variable azimuth scan can be employed to provide coverage with a horizontal resolution of 500 km by 500 km or better as shown

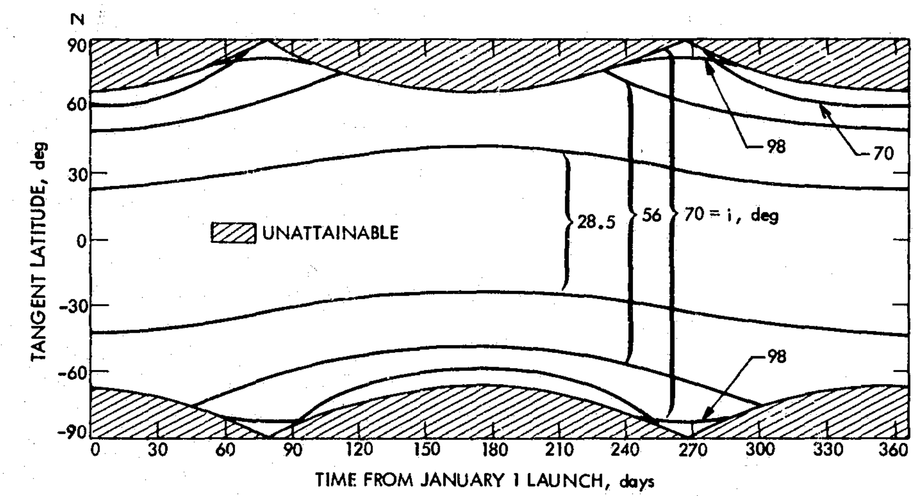

Fig. 14. Effect of orbit inclination on latitude coverage envelope for solar occultation (orbital height = 600 km)

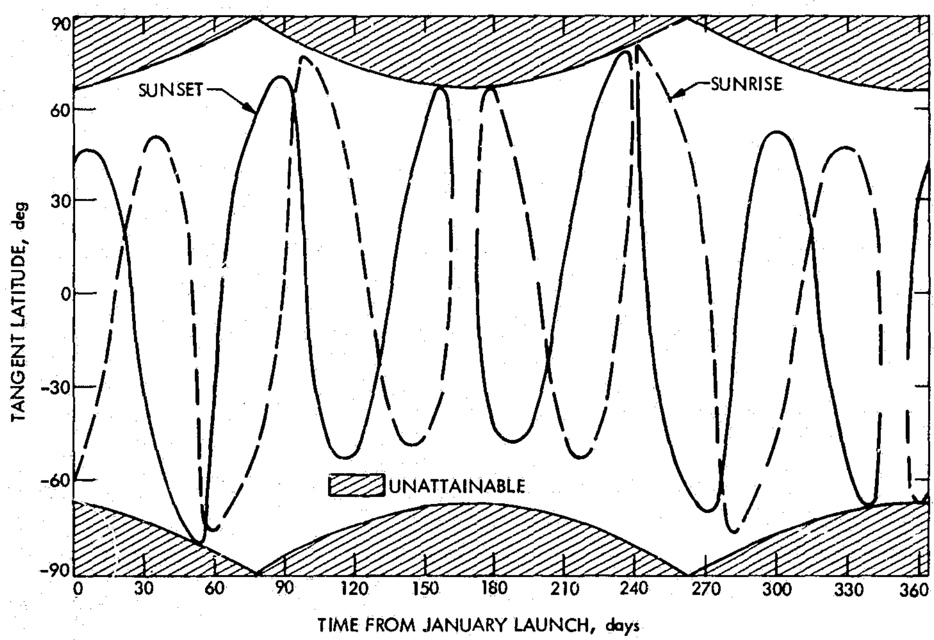

Fig. 15. Latitude coverage for solar occultation during one-year mission (orbital inclination = 56 deg, orbital height = 600 km)

in Fig. 19. These data are based on having one profile measurement every 12 seconds and 7 such measurements per scan sweep distributed from a scan azimuth of +90 deg to −90 deg. A vertical resolution of 3 km can be achieved for each of these points. Note that the number of points that represent obtainable profiles is approximately 3500 in each hemisphere per day. This wealth of data would allow for detailed, four-dimensional (i.e., latitude, longitude, altitude, and time) analysis of the atmospheric processes to be conducted.

Diurnal variability of regional (500-km by 500-km) scale phenomena could also be studied. Figure 20 illustrates the

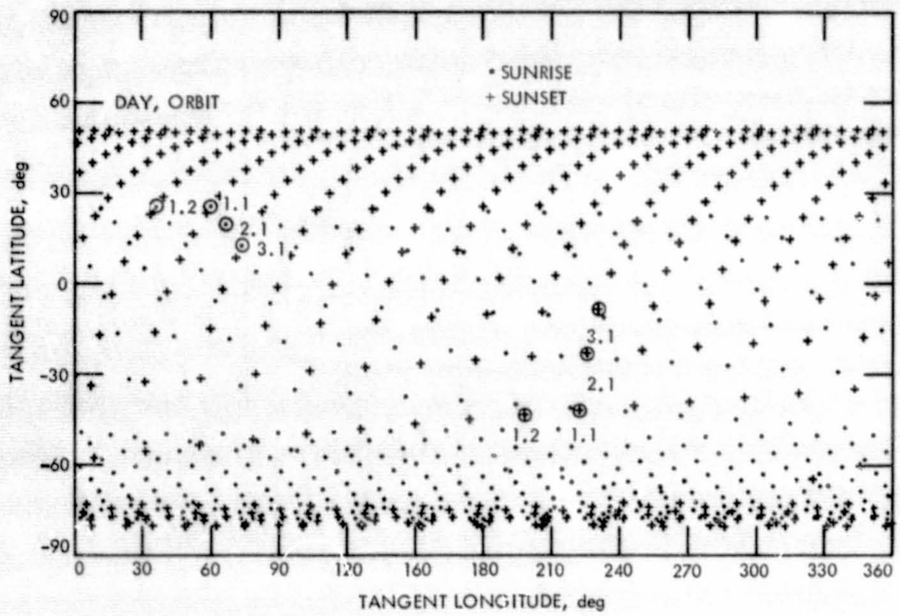

Fig. 16. Solar occultation geographical coverage (orbital inclination = 56 deg, orbital height = 600 km) for 30 days (March)

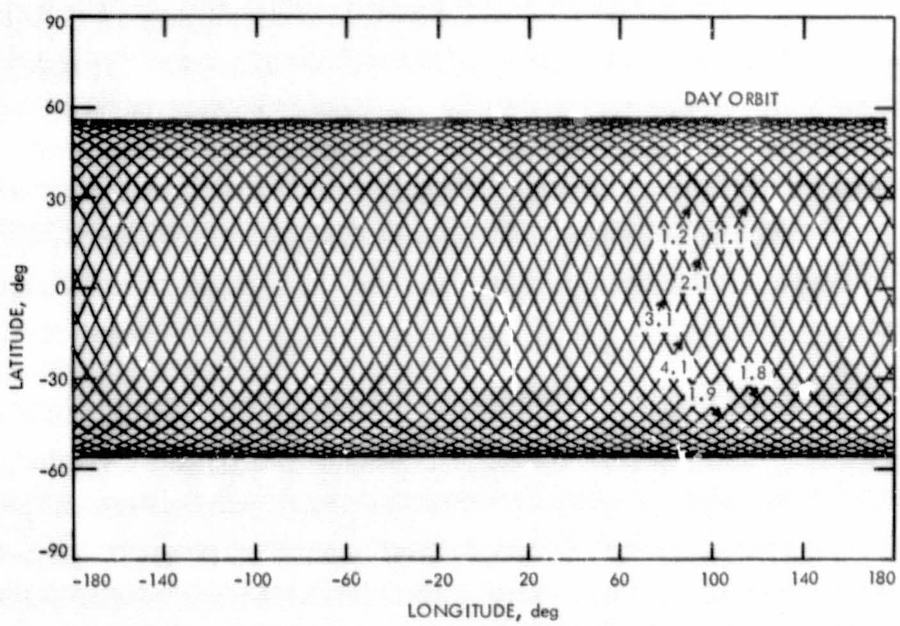

Fig. 17. Geographical coverage of limb emission sensor with fixed azimuth angle = 0 deg (orbital inclination = 56 deg, orbital height = 600 km) for three-day repeat cycle

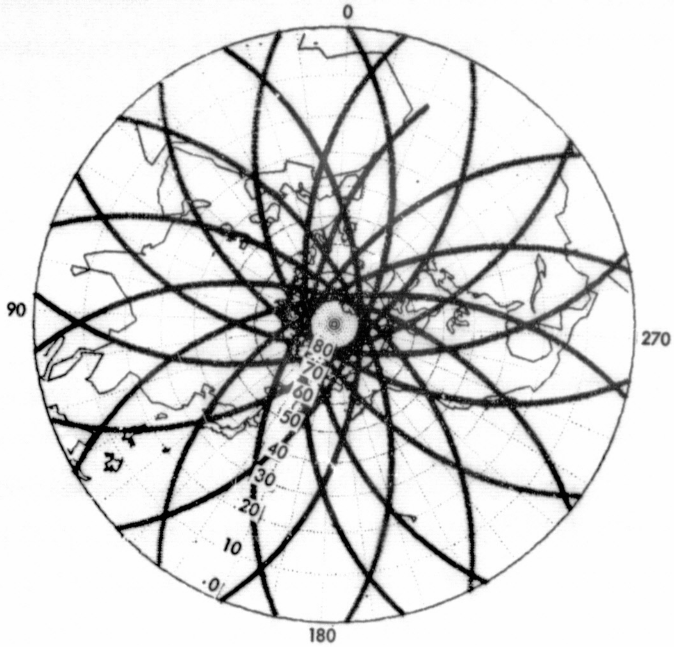

Fig. 18. Limb scanner geographical coverage (Northern Hemisphere) with fixed azimuth angle = 90 deg (orbital inclination = 56 deg, orbital height = 600 km) for one day

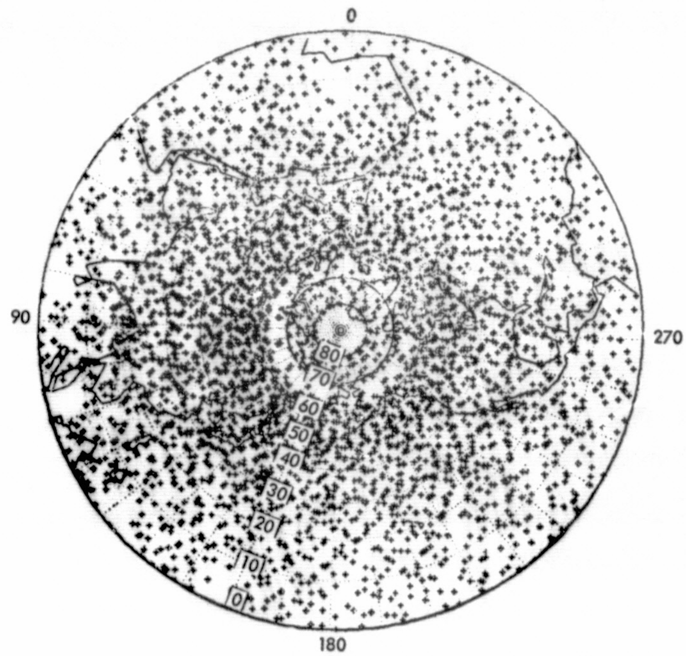

Fig. 19. Limb scanner geograhical coverage (Northern Hemisphere) with variable azimuth scan (orbital inclination = 56 deg, orbital height = 600 km) for one day

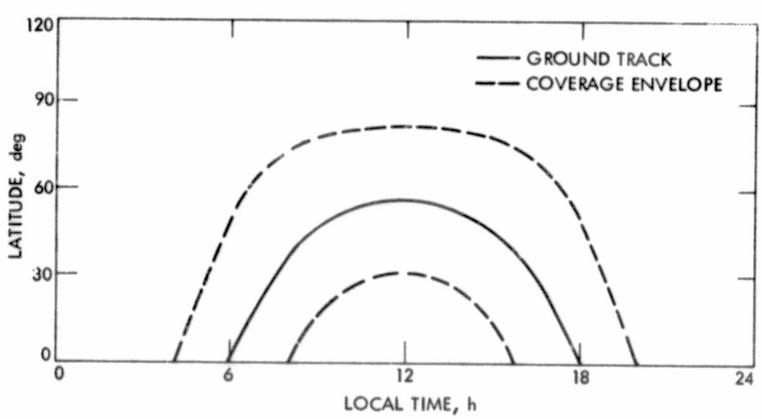

Fig. 20. Regional diurnal coverage capability with limb emission and variable azimuth scan (orbital inclination = 56 deg, orbital height = 600 km) for one day

number of local hours as a function of latitude that can be observed over a region in a day. A total of 6 hours (e.g., 5:24, 6:00, and 7:36 on ascending orbits, and 16:24, 18:00, and 19:36 on descending orbits) in the equatorial regions, and up to total 12 hours at high latitudes can be covered during the mission because the orbit precesses about 1/3 hour each day, covering all hours in 36 days. The orbit precession rate is a strong function of inclination. Figure 21 presents data on the time required to precess through all local hours at the equator as a function of orbit inclination. The 56-deg and 70-deg orbits require 36 days and 52 days, respectively, to precess through all local hours. Sun-synchronous orbits do not precess with respect to the Earth-Sun line and, therefore, remain at the same local time throughout the mission. Since complete diurnal coverage is desirable, orbits that precess as rapidly as possible and still have adequate latitudinal coverage would seem to be the best candidates for the UARS missions.

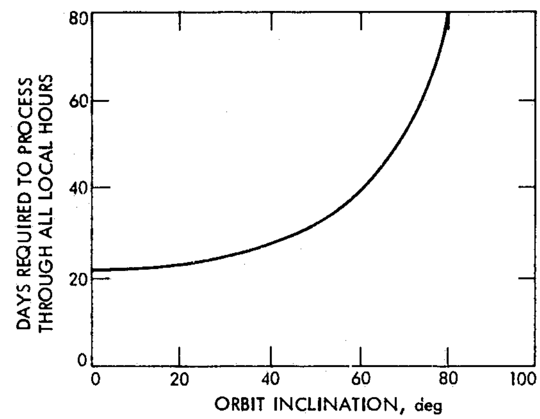

Fig. 21. Effect of orbit inclination on time to precess through all local hours at the equator (orbital height = 600 km)

Part III. Program Approach

I. Approach

A. Science Team Organization

It is expected that overall direction of scientific activities within the various UARS missions will be directed and coordinated through a Science Team composed of the experimental and theoretical Principal Investigators. Because the UARS Program is built around long-term scientific objectives, there is a need to ensure not only a balance between theory and observation, but also mechanisms for evolution of the project goals and Science Team membership. Many of the ideas presented here have developed in connection with Atmospheric Explorer, acknowledged to be one of the most scientifically productive satellite projects yet flown.

The choice of Principal Investigators (P.I.) to participate in the first UARS mission will be made by NASA from proposals called for by an Announcement of Opportunity. It is expected that the Principal Investigators selected will be of two types, with some overlap. The Experiment P.I.s, and their Co-Investigators (C.-I.) will have the usual responsibility for developing a particular instrument and conducting analyses of their observations to yield quantities of geophysical interest. In addition, it is expected that the experiment teams will participate in extensive data analysis and interpretation using relevant theory.

Another category of Principal Investigator, and associated Co-Investigators, will include theoreticians with expertise spanning a broad range of interests relevant to the upper atmosphere, as well as the interpretation of experimental data. On the one side, there is a need for theoreticians to be involved in the conversion of radiance data into accurate geophysical information. On the other, geophysically oriented theoreticians are needed to conduct extensive diagnostic studies, to develop new theory, and to verify theory by comparing the results of complex simulation models with the actual behavior and structure of the atmosphere.

An overlap in activities involving experimentalists and theoreticians occurs at the point where data are analyzed and interpreted. This interface is essential to provide the contact needed to involve each group in the other's activity. Within the overall structure of the team, such interfacing appears to be best satisfied through the establishment of internal working groups that attack particular problems facing the science team.

The Science Team should consist of the Project Scientist and Principal Investigators. The Project Scientist and one Principal Investigator, selected by all the Principal Investigators, will serve as cochairpersons of the team. It will be the responsibility of the team to organize the resources of the UARS satellites and the associated theoretical teams in such a way as to optimize the scientific return of the missions authorized at any particular time.

Guest investigators may also be valuable to the overall project. Following the establishment of the Science Team, a separate Announcement of Opportunity followed by the selection of individuals or teams useful to the program may be considered.

It is expected that ad hoc and permanent working groups will be established to identify problems facing the team. The Chairperson of a Working Group should be a Principal Investigator. Membership on this working group will not be restricted to the P.I.s, but extend to C.-I.s, guest investigators, or others who have specialized knowledge required by the group. Adequate funds should be available to cover travel and other expenses of the working groups.

B. Data Exchange

Experiment Principal Investigators are responsible for the operation of their instrument and the interpretation of their data in terms of geophysical quantities (e.g., concentrations, temperature, and winds). Initially, many of the theoreticians may be involved in developing and validating the various inversion schemes that will be required. Later, routine production of data may involve only the experimenter as an overseer to the central data handling and computing facility.

In general, the data acquired by the individual instruments is to be made available to all P.I.s, experimental or theoretical, directly following its acquisition. Research projects involving one or more instruments or the development of theoretical models should be sponsored by individual P.I.s and approved by the Science Team. Participation in these projects is open to all Science Team members and others, including C.-I.s, guest investigators, and members of individual teams. For sufficiently broad projects, an ad hoc working group may be established by the Science Team.

The first publication of data from any instrument should normally include authorship for the experimental P.I. or his designated alternate, if he so desires.

During long-term missions, it may be appropriate that individuals change roles. A Principal Investigator may elect to become a Co-Investigator after a certain phase of the mission is complete. To do so, the Principal Investigator will recommend a Co-Investigator to become Principal Investigator with the approval of NASA headquarters. The Principal Investigator may then become a Co-Investigator.

It is anticipated that the initial Science Team will be drawn from P.I.s associated with the first UARS mission. Selection of the second mission P.I.s will enlarge the team. As particular missions terminate, it is expected that the associated P.I.s and their teams will be primarily concerned with data analysis and interpretation. As such, they should have no direct voice in the on-going affairs of the Science Team except to the extent that they can contribute with specific research projects or working groups.

It is expected that the Science Team will make recommendations of the scientific objectives of future missions in the program. Approval of these objectives and their implementation will come from NASA headquarters.

C. Mission Plans

In this section, two candidate UARS missions are presented that satisfy a number of key scientific objectives and fit the evolutionary expectations of the overall program. In arriving at the two missions, it has been necessary to take into account various aspects of spacecraft and experiment technology, funding considerations for a two-mission new start, and the extent to which two simultaneous satellite missions enhance the overall scientific yield. It should be remembered that the mission planning aspect of the SWG's report is intended as a feasibility exercise. Given a basic set of high-priority scientific objectives, a set of measurement requirements has been generated. Through reference to existing and developing instruments, it is possible to select an experiment payload that satisfies basic constraints with respect to such considerations as weight, volume, power, data rate, orbit, orbit changes, and pointing accuracy. Further, with some iteration, it is possible to arrive at a set of mission objectives that are satisfied by the adopted payload. However, the candidate payload derived in this manner is not necessarily representative of the final payload actually flown, owing to a number of factors including cost, revision of science objectives, and especially technological progress improving basic measurement capability.

The key philosophical elements used to help define the two initial UARS missions include:

(1) Evolutionary mission objectives. It is expected that knowledge gained from successive missions will compound, leading to progressive changes in the program objectives.

(2) Evolutionary instrumentation. New and improved instruments will appear in the course of the program in response to development funding.

(3) Eastern Test Range launch for the first mission.

(4) Space Shuttle launch and possible retrieval or refurbishment.

(5) Cryogenic limit for mission lifetime. Currently set at 18 months for limited duty cycle of key instruments.

There are also variables associated with a two-satellite mission. These include:

(1) Temporal overlap. To what extent is it desirable to have the two spacecraft operating simultaneously?

(2) How long should each mission last?

(3) What choice of complementary orbits would yield maximum scientific return?

The SWG recognizes the great complexity involved in mission planning and has not had the time or resources needed for a complete mission definition study. The missions described below meet initial requirements with respect to the basic UARSP guidelines and give a fair idea of the potential scientific benefits that would be derived from the first phase of the program.

1. **First mission**

a. Objectives. The various domains of atmospheric research — radiation, chemistry, and dynamics — and the coupling between them, should each receive sufficient attention in the first mission to permit an advance in the overall understanding of the upper atmosphere. However, the measurement capability anticipated for the first mission, plus the orbit possibilities dictated by an Eastern Test Range launch, form a set of constraints that suggest that the first UARS mission should be aimed at studies of upper atmosphere energetics, including radiative energy input and loss, and chemical interactions of the middle atmosphere except at high latitudes. Owing to the developmental nature of the wind sensors, dynamics studies will be initiated on this mission, but probably cannot be pursued in depth. On the other hand, the relatively short (34 days) time needed for a complete latitude/local-time survey makes this a useful set of variables to emphasize; the eleven cycles of this set over one year will allow relatively unambiguous separation of the seasonal components of the latitude/local-time variation up to high midlatitudes in both hemispheres. Interaction and coupling between atmospheric regions and processes will also be emphasized on the first mission, although the uncertainty with regard to the capability of wind measurements may reduce to some extent the study of interactions involving dynamics and transport.

Strong scientific interest in studying upper atmospheric phenomena over the Northern Hemisphere winter (related to stratospheric warming events and the abundance of correlative data relative to the Southern Hemisphere) indicates that an early fall launch date would be most appropriate. With an anticipated measurement lifetime of one and a half years, the fall launch would provide data over two Northern Hemisphere winters.

b. Instruments. A combination of instruments similar to that shown in Table 6, Section I of Part II, is expected to form the basis for the first UARS mission. These instruments, in concert, will provide satisfactory data on the solar energy input, the energetics and most of the important photochemical species of the upper atmosphere, as well as initial data on wind fields for studies of the dynamics. With the possible exception of the laser heterodyne radiometer (LHR), the far IR spectrometer (FIRS), and the microwave limb sounder (MLS), these instruments will all have been developed and flown on satellites prior to the first UARS mission. The LHR, FIRS, and MLS are currently being developed for balloon use and will require additional development to be suitable for use on a free-flying spacecraft. However, overall it will be possible to plan for a relatively early launch date and conduct a useful set of measurements without the complication of extensive instrument development in series with the schedule.

The limiting factor in the lifetime projected for the first UARS mission appears to be the lifetime of the stored cryogens required for those instruments with cooled detectors. The technology exists now to permit operation for at least one and a half years (with some weight penalty) for all these instruments, and two years for most of them.

c. Orbit. In accordance with the requirement for launching from the Space Shuttle, and acknowledging the present uncertainty in the early scheduling of shuttle operations from the Western Test Range (WTR), it is anticipated that the initial UARS mission will be launched from the Eastern Test Range (ETR). Use of this facility limits the inclination of the orbit to a maximum of 56 deg; however, the limb scanning instruments measure in a volume of the atmosphere approximately 23 deg away from the satellite (when the satellite is at an altitude of 600 km), so latitudes between ±79 deg can be observed. This is adequate geographic coverage for many of the scientific requirements, and the orbital inclination permits a complete local-time/latitude coverage in about 34 days. Thus, it is felt that the added complication of an orbit plane adjustment is not justified for the initial mission.

Considering the remote sensors included in the anticipated payload, a circular orbit between 400 and 600 km appears to offer the optimum trade-off between field-of-view, resolution, and lifetime in orbit. At altitudes below 500 to 550 km, the spacecraft will require a number of burns of the propulsion motor to maintain the orbit against atmospheric drag over one year. The final choice of altitude must be based on the appropriate atmospheric density for the specific part of the solar cycle, the spacecraft mass, area and drag coefficient, and effect on the instruments of motor burn operations.

The nadir-looking instruments (e.g., the cloud amount/temperature sensor) impose another requirement on the orbit. Since the limb sounder instruments and the nadir instruments do not look in the same place at the same time, the orbit parameters must be adjusted to allow correlation of the data on successive orbits. Thus, cloud characteristics are measured about 90 minutes out of phase with the vertical profiles, requiring that both diurnal and real-time effects be properly considered in the data analysis. The necessary orbit adjustments are accomplished primarily by incremental changes in orbital altitude.

Table 9 gives a summary of the first UARS mission objectives, instruments, orbit, and launch.

Table 9. First mission summary

Parameter	Description
Objectives	
	Study of energetics and chemistry at low, mid, and moderately high latitudes, with emphasis on solar irradiation
	Initial studies of dynamics and transport
	Initial studies of coupling and interactions among processes and atmospheric regions
	Studies of the seasonal variation in the local-time/latitude behavior of the upper atmosphere
Instruments	(see Table 6)
	Relatively small instruments, requiring minimum development
	Cooled detectors for some sensors, possibly cooled optics for some
Orbit	
	56-deg inclination
	Circular at 400 to 600 km
Launch	
	Eastern Test Range
	September, 1983
	Space Transportation System (Shuttle)
Lifetime	
	18 Months

2. **Second mission.** The second UARS mission has been defined using the following guidelines:

(1) The Western Test Range will be available for Shuttle operations by 1984.

(2) The initial mission lifetime is at least 18 months.

(3) There is a scientific need for 6 months overlap between the missions. The overlap period should be timed so that double coverage occurs during Northern Hemisphere winter. This decision is based on the need to observe mechanisms associated with stratospheric warmings with pole-to-equator coverage of all energy sources. In addition, the overlap period will assure validation of calibrations and continuity of coverage.

The availability of WTR for second mission launch operations allows high-inclination orbits, which permit observations at high latitudes. Prominent among these processes to be studied are the effects of the storage of photochemically active species during the polar night, and the effect of long periods of sunlight on photochemical processes. It is necessary to note that in-depth study of these species will require emission sensors, some of which may not be available for the first high-inclination UARS mission, but their development and use during the lifetime of the project is anticipated. The second mission, therefore, should provide many of the data necessary for initial studies of these phenomena. Also to be emphasized is the effect of the energy inputs from the magnetosphere and the distribution of this energy to other regions of the atmosphere. This leads also to the question of the interactions between magnetospheric energy inputs (e.g., joule heating and particle precipitation) and thermally driven, or sunlight sensitive, phenomena.

In addition to providing greater geographical coverage, the second UARS mission will provide both temporal overlap with, and temporal extension of, the data set begun on the first mission. The overlap and extension are both necessary to the study of long-term trends in middle atmospheric phenomena: the extension is obviously necessary to provide a sufficiently long data base to establish trends and to compare inter-annual variations, while the overlap is needed to give confidence in the accuracies of data from sensors on the two spacecraft. The overlap will also enhance those studies involving local time sensitivity, as the local time of launch of the second mission can be chosen to complement that of the first mission. The overlap in the two missions is recommended to be at least six months.

A summary of the second mission is given in Table 10.

3. **Subsequent missions.** New instrumentation developed during the lifetime of the UARS program offers the potential for upgrading the measurement capability on subsequent missions. For example, the development of the cryogenically-cooled IR spectrometer limb scanner (CLIR) for the AMPS program makes possible the inclusion of this sensor on the later UARS missions to obtain data on parameters that might otherwise be unobtainable. The limited duty cycle (~15% currently projected) for the spectrometer imposed by the cryogenics over the mission lifetime means that many of the species-specific instruments would still be required to provide the necessary temporal coverage, but the sum of the data acquired from the upgraded payload would go much further in meeting the more stringent of the scientific requirements. Other measurements that probably will benefit from improved instrumentation on later flights will be those of the chemical species HCl, ClO, and OH.

Similar uncertainties exist for the upper atmosphere wind measurements on the early missions, and it is anticipated that

Table 10. Second mission summary

Parameter	Description
Objectives	
	Continue studies of energetics, chemistry, dynamics and coupling begun on the first mission
	Study effects of magnetospheric energy inputs (e.g., joule heating and particle precipitation) on upper atmosphere
	Provide six months overlap with the first mission to insure continuity of coverage, validate instrument calibrations, enhance diurnal coverage, and give complete equator to pole coverage
	Initial study of polar night storage phenomena for chemically active species
	Study effect of prolonged sunlight on atmospheric chemistry and transport
Instruments	
	Basic instrumentation similar to the first mission
	Improved wind measuring instruments
	Instruments to measure magnetospheric energy inputs (e.g., particle flux detectors, electric field sensor, and magnetometer)
	Improved emission sensors
Orbit	
	70-deg inclination
	Circular at 500 to 600 km
Launch	
	Western Test Range
	Second quarter, 1984
	Space Transportation System (Shuttle)
Lifetime	
	18 months

suitable sensors will be developed in time for use on later missions for this very important parameter.

Orbital inclinations of 70 deg permit complete geographical coverage using the limb scanning instruments. At this inclination, it takes about 50 days for a complete local-time/latitude coverage, so it may prove desirable to invoke simultaneous coverage by at least two spacecraft, appropriately phased in local time, to reduce this period to about 25 days. Orbital inclinations higher than 70 deg offer no advantages in geographic coverage for most of the sensors to be used, and the lower orbital plane precession rates increase the time required for complete local-time/latitude coverage to unacceptable levels for local time studies. Lower inclinations, on the other hand, offer the possibility of studying special phenomena. An equatorial orbit, for example, would provide intensive coverage in the tropics for study of equatorial waves, phenomena associated with the Hadley circulation, and convective activity in the region of the intertropical convergence zone.

Studies are now underway to determine the potential for retrieval of the UARS spacecraft for refurbishment and reuse, or even the possible refurbishment in orbit. If it appears that the satellites can be reused, the design of the satellites and instruments for the first missions should reflect the incorporation of more sophisticated and larger instruments than are anticipated initially.

Figure 22 shows the mission sequence related to the coverage it provides over the solar cycle. The program outlined here yields coverage of solar activity effects only on the approach to the minimum of the eleven-year cycle, and a continuation of the program is desirable to allow comprehensive study of the upper atmosphere over a complete solar cycle. Also shown in Fig. 22 are other satellites expected to provide atmospheric data prior to the first UARS launch. Knowledge gained from these flights will probably change some of the emphasis of the UARS program and details of the mission proposals. The AMPS missions are expected to continue into the time frame of the UARS, and these also will probably alter the details of the UARS mission scenario as complementary uses of the two programs evolve.

Table 11 provides a summary of possible follow-on mission objectives.

D. Orbit Requirements for First Two UARS Missions

1. First UARS mission orbit. In line with the requirement for launching from the Space Shuttle, and acknowledging the present uncertainty in the early scheduling of Shuttle operations from the Western Test Range (WTR), it is anticipated that at least the initial UARS mission will go from the Eastern Test Range (ETR). Use of this facility limits the inclination of the orbit to a maximum of 56 deg; however, the limb scanning instruments measure in a volume of the atmosphere approximately 23 deg away from the spacecraft (where the spacecraft is at an altitude of 600 km), so latitudes between ±79 deg can be observed. This is adequate geographic coverage for most of the scientific requirements and the orbital inclination permits a complete local-time/latitude coverage in about 36 days. Thus it is felt that the added complication of an orbit plane adjustment is not justified for the initial mission.

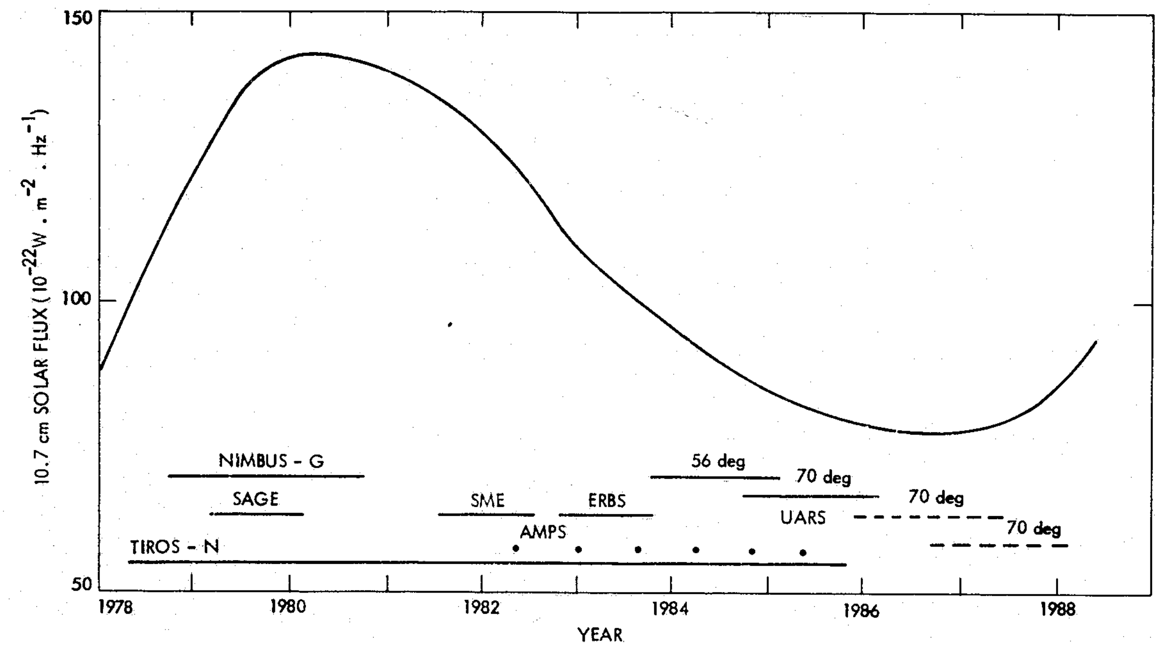

Fig. 22. Mission sequence in relation to the solar cycle

Table 11. Follow-on missions summary

Parameter	Description
Objectives	
	Extend the data coverage in time to permit study of atmospheric phenomena over a solar cycle
	Extend the data coverage in time to evaluate possible long-term anthropogenic perturbations to the upper atmosphere
	Extend the data acquisition to approach the "desired" accuracies, resolutions, and altitude ranges (e.g., for chemical species and winds) as new instruments become available
	Provide better temporal and spatial coverage by the use of multiple spacecraft in orbit simultaneously
	Enhance the study of the lower thermosphere in recognition of possible coupling mechanisms with the mesosphere and stratosphere
	Study of interannual variability of upper atmosphere

Considering the remote sensors included in the anticipated payload, a circular orbit between 400 and and 650 km appears to offer the optimum trade-off between field of view, resolution, and lifetime in orbit. At altitudes below 500 to 550 km, the spacecraft will require a number of burns of a propulsion motor to maintain the orbit against atmospheric drag over one year. The final choice of altitude must factor in the appropriate atmospheric density for the specific part of the solar cycle, the spacecraft mass, area and drag coefficient, and effect on the measurements of motor burn operations.

2. **Second UARS mission orbit.** It is assumed that the second mission will be launched after the WTR becomes available for shuttle operations. Thus, it is anticipated that the orbital inclination will be increased to 70 deg to permit complete coverage of the geographic pole (using the limb scanning instruments) and the additional possible advantages of direct overflight of the higher latitudes. At this inclination, it takes about 52 days for a complete local-time/latitude coverage, so it may prove desirable to invoke simultaneous coverage by at least two spacecraft, approximately phased in local time, to reduce this period to about 26 days. Orbital inclinations higher than 70 deg offer no advantages in geographic coverage for most of the sensors to be used, and the associated lower orbital plane precision rates increase the time required for complete local-time/latitude coverage to unacceptable levels for local time studies.

The orbit-altitude selection for the second UARS will be based on the same criteria as for the first mission. An altitude between 400 to 650 km (circular) appears to be most desirable.

The second UARS mission will provide temporal and spatial overlap with the data set begun on the first mission. This overlap (about 6 months) will give confidence in the accuracies of data from sensors on different spacecraft. The launch time of the second UARS can also be selected to complement the local time coverage (and latitude coverage for solar occultations) of the first mission for scientific studies.

E. Supportive Observations and Theory

When one considers the implementation of a program of supportive observations on a problem as large and complex as the study of the atmosphere, it soon becomes clear that a program supported solely by NASA becomes impractical, if not impossible. A plan to implement an adequate set of experiments must then include extensive involvement in cooperative programs that include not only other agencies, but groups in other countries. A requirement for the program then is a liaison office that keeps the UARS Program (and indeed, other solar-terrestrial programs) in close contact with the remainder of the community. An attractive vehicle for the coordination efforts may be found in the developing MAP (Middle Atmospheric Program) efforts.

Programs with which cooperation needs to be maintained and for which support needs to be supplied where appropriate include the ground based programs, particularly the emerging sounding programs that use incoherent and coherent scatter phenomenon to measure winds, the balloon programs that provide both stratospheric platforms and circulation data, and rocket programs that have provided and continue to provide much of our mesospheric data.

Since the UARS will be forced to rely entirely on remote probes for its sampling of the stratosphere, it is important that methods of confirming the deduced results should be available. While these methods are usually referred to as "ground truth" measurements, in many cases it will be necessary to obtain "ground truth" within the region observed.

For example, experiments to confirm the accuracy of the deduced profiles are crucial to establish confidence in the inversion techniques to be applied to the radiance profiles used to obtain temperature. These experiments will involve a number of expeditions using sounding rockets and balloons to establish the validity of the results. A number of these programs will be required to establish that the deduced results are truly representative of the atmospheric conditions.

The UARS concept calls for the deduction of stratospheric winds from the temperature profiles. These measurements will be closely coupled with the predictions of the circulation models developed by the theoretical groups.

The use of superpressure and isentropic balloons and their tracking can be of considerable utility in the validation of these deduced measurements. On the basis of these previous arguments, it is important that NASA maintain viable balloon and sounding rocket programs that are funded to the extent that they not only remain viable programs, but in addition are able to participate fully in cooperative experiments.

The techniques mentioned, while they promise to be very useful, are not able to address in detail one very important aspect of the atmospheric motion problems: the need to measure vertical motions. Vertical motion studies are not yet developed except in a few isolated cases where scattering data are available, but with the rapid development of new lasers, laser techniques should soon be developed. A system that has demonstrated the capability of at least vertical motion measurements is a combination of coherent and incoherent radio scattering techniques. These two techniques have demonstrated the capability of making measurements throughout the atmosphere. In the presently available systems, there is an apparent gap in capability in the region between 30 km and 80 km, but closure of this gap by measuring the power-aperture product of the systems appears to be straightforward. NASA should take steps to insure the viability of these systems in the next decade either through cooperative efforts or direct funding.

The concept of the UARS is such that relatively simple instruments will be aboard for the monitoring of a variety of selected species. There will be times when it will be desirable to obtain much more extensive sets of measurements. This need can be filled by judicious use of the Shuttle. Payloads that involve extensive measurement capabilities such as will be available on the AMPS payload and on some of the Spacelab payloads can be used in coordination with UARS to good effect.

A final area in which coordination of measurements is required is the relation of UARS to other solar-terrestrial experiments. Systems of satellites such as the OPEN series can, when coupled with UARS, represent the most complete set of measurements yet devised to track the energy flows from the Sun to the Earth. It is important that, as the OPEN series and other STR satellites are developed, the opportunities available from proper coordination be kept in mind.

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Appendix
Instruments and Instrument Development

Table A-1 lists limb scanning instruments matched to the measurement requirements taken from Table 4. Generic names are used in Table A-1 rather than acronyms specific to individual instruments. The capabilities of the instruments have been obtained by a survey of principal investigators from various NASA programs. In performing the matching exercise leading to Table A-1, existing instruments are given preference over instruments that have not yet flown on spacecraft. Emission instruments are given preference over occultation instruments because of their shorter time scale for obtaining full global coverage. Species-specific instruments are given preference over such survey instruments as spectrometers because of the higher sizes, weights, and data rates required by the latter.

For the measurements listed in Table A-1 under sections A, B, and C, existing radiometers are available. In a few cases, however, the instrument given in column three of Table A-1 does not quite meet the "adequate" measurement standard, or there is only an occultation instrument available. For the measurement of mesospheric winds, present modulated gas cell radiometers can measure only one component of the wind at an arbitrary limb tangent point, although concepts do exist that may allow such an instrument, in principle, to measure both wind components. A microwave instrument could measure both components at any prespecified limb tangent point to altitudes as high as 100 km, but the instrument has not yet been flown and therefore appears in parentheses in Table A-1. A microwave instrument appears to be the most promising emission radiometer for measurement of mesospheric ozone. The 1.27-μ emission radiometer on SME will be used to infer mesospheric ozone, but the primary function of this instrument is for determining radiation balance. A UV limb backscatter instrument used in the absorption mode can also measure mesospheric ozone, but only in the daytime.

For the species in Table A-1, section D, there are as yet no proven instruments in the sense that these species have not yet been measured in the upper atmosphere by remote sensing techniques. Nevertheless, it is important to measure these species as part of the UARS Program. The potential for microwave and laser heterodyne radiometers to measure these species is indicated in Table A-1. The microwave instrument operates in emission, while the laser heterodyne radiometer operates in solar occultation. These instruments will have balloon test flights in the next several years. There is also the potential for measurement of OH using an occultation radiometer.

Table A-2 shows the projected capability of three survey-type instruments: a cryogenic emission spectrometer, a far-IR spectrometer, and an occultation spectrometer. The occultation spectrometer has been proven on balloon flights, and will be flown on Spacelab 1. The cryogenic spectrometer is under development and its capabilities are untested. To operate in the middle IR, the entire instrument must be cooled. The far IR spectrometer requires cooling of the detector, but only modest cooling of the optics. The capabilities of a far IR spectrometer will be tested from a balloon platform.

The three spectrometers in Table A-2 are most appropriate for conducting surveys of the upper atmosphere to identify the presence of new and/or unsuspected species, as well as for examining local photochemistry by observing simultaneously the largest set of molecules possible. However, they also may be needed as part of the UARS program, either on Spacelab in

Table A-1. Species- and quantity-specific instruments matched to requirements

Quantity	Measurement requirement	Matching instrument
	A. Irradiance and dynamics	
Solar Flux	See Table 1	UV spectrometer
Temperature	1 K precision, 15–70 km 2 K precision, 65–100 km	Filter radiometer, 1–2 K, 8–70 km Modulated gas cell radiometer, 1.5 K, 15–90 km
Wind	2 ms^{-1}, 15–60 km 10 ms^{-1}, 65–100 km	Doppler interferometer, 5 ms^{-1}, 15–55 km Modulated gas cell radiometer[a] 5 ms^{-1}, 60–110 km (microwave limb sounder, 5 ms^{-1}, 70–100 km)
Cloud cover	10%	IR nadir radiometer
Cloud-top temperature	3 K accuracy/1 K precision	IR nadir radiometer
	B. Species measured by existing emission radiometers	
O_3	10%, tropopause–60 km 25%, 60–90 km	Filter radiometer 5–10%, trop.–65 km 1.2 μ emission spectrometer[b] 50–90 km (microwave limb sounder, 25%, 25–95 km)
H_2O	10%, tropopause–70 km	Modulated gas cell radiometer, 10%, 15–100 km Filter radiometer, 15%, 10-80 km
CH_4	20%, tropopause–60 km	Modulated gas cell radiometer, 10%, 15–60 km Filter radiometer, 15%, 10–50 km
N_2O	20%, tropopause–40 km	Modulated gas cell radiometer, 10%, 15–60 km Filter radiometer, 20%, 10–50 km
CO	10%, 20–60 km	Modulated gas cell radiometer, 10%, 15–60 km
HNO_3	10%, 20–30 km	Filter radiometer, 10–15%, 10–40 km
NO (strato)	10%, 25–60 km	Modulated gas cell radiometer, 10%, 15–60 km
NO (meso)	10%, 60–100 km	Circularly variable filter radiometer, 10%, 70–120 km
NO_2	10%, 25–60 km	Filter radiometer, 15%, 10–40 km
	C. Species for which occultation radiometers presently exist	
HCl	10%, 20–50 km	Occultation radiometer, 10%, 10–40 km
HF	10%, 20–50 km	Occultation radiometer, 10%, 10–40 km
CF_2Cl_2	20%, tropopause–40 km	Occultation radiometer, 10%, 10–30 km
	D. Species for which instrument development is required	
$CFCl_3$	20%, tropopause–35 km	Laser heterodyne radiometer, 0.05 ppb, 10–45 km
CH_3Cl	20%, tropopause–40 km	Laser heterodyne radiometer, 0.02 ppb, 25–45 km
CH_3CCl_3	20%, tropopause–40 km	(None)
OH	10%, 25–40 km 25%, 60–90 km	Microwave limb sounder, 45–80 km Occultation radiometer, 15–40 km
ClO	10%, 25–40 km	Microwave limb sounder, 0.3 ppb, 25–45 km Laser heterodyne radiometer, 25–40 km

Table A-1 (cont)

Quantity	Measurement requirement	Matching instrument
$O(^3P)$	10%, 60–90 km	Microwave limb sounder, 45–120 km
H_2O_2	10%, 25–50 km	Microwave limb sounder, 0.1 ppb, 25–50 km Laser heterodyne radiometer, 10–40 km
N_2O_5	10%, 20–30 km	(None)
$ClONO_2$	10%, 20–30 km	Laser heterodyne radiometer, 0.3 ppb, 20–45 km
$O(^1D)$	10%, 20–90 km	(None)
$N(^4S)$, $N(^2D)$	25%, 60–90 km	(None)
HO_2	10%, 25–40 km	Laser heterodyne radiometer, 25–40 km
HOCl		(None)
SO_2		(None)
OCS		(None)
H_2SO_4		(None)

[a]Cannot resolve wind components; can measure only magnitude of radial component at an arbitrary azimuth angle; the MLS may therefore be required for mesopheric winds.

[b]Accuracy of this method is questionable. The UV method used on SME is applicable for daytime only. The MLS is therefore listed as a potential emission instrument for mesospheric ozone.

conjunction with the UARS or as instruments flying on UARS, to measure species for which no specific instrument is available. The present capabilities of the occultation spectrometer, and the promised capabilities of the cryogenic spectrometer and far IR spectrometer, in general exceed those of radiometers and fill in gaps where no specific instrument now exists.

There are significant limitations to the use of survey-type IR spectrometers on a free-flying satellite: the capabilities of the spacecraft-ground data transmission system and the necessity for a large cryogenic cooling system for IR emission spectrometers. The TDRSS data system, which must be used in the time frame of the UARS missions, requires a data rate of no more than 50 kbs^{-1} for continuous access channels. The single, high-data-rate channel on TDRSS is limited to one user at a time, and is subject to scheduling limitations. The duty cycle of the cryogenic limb emission spectrometer will most likely be limited by the lifetime of the cryogenic system.

Both Payloads A (Table 6) and B (Table 7) were derived using the instrument capabilities given in Tables A-1 and A-2. Payload A is based on the use of species-specific instruments wherever the instrument capability matches a measurement requirement. Payload B is derived on the basis of a cryogenic emission spectrometer as a core instrument. The matching process is illustrated here for the case of Payload A. Emission radiometers are given preference over occultation radiometers. The projected capabilities of the microwave and laser heterodyne radiometers are used for Payload A, with the exception of OH and $O(^3P)$, since the microwave capability for these species will probably not be available for the first UARS mission. After using all the available best-match instruments in Table A-1, the list of species-specific instruments in the payload fails to fulfill the requirements for measurement of HCl, OH, and $O(^3P)$ in emission, and for measurement of CH_3CCl_3 in emission or occultation.

There are no species-specific instruments under development for measurement of HCl, OH, and $O(^3P)$ in emission, other than the microwave limb sounder. In the absence of these developments, it is necessary to add a spectrometer from Table A-2 to Payload A. The far-IR spectrometer advertises the capability to measure HCl, OH, and $O(^3P)$ in emission. It does not have a stringent requirement for cooling as does the mid-IR emission spectrometer, and is not likely to have duty cycle limitations. The far-IR data rate for continuous operation is also much lower than for the cryogenic spectrometer.

Table A-2. Capabilities of survey-type instruments

Instrument	Species measured
Occultation spectrometer (ATMOS)	HCl, HF, HBr, $CFCl_3$, CF_2Cl_2, CH_3Cl, CH_3F, $CHCl_3$, CH_3Br, $ClONO_2$, $FONO_2$, CH_4, N_2O, H_2O, HDO, CO, O_3, H_2O_2, N_2O_5, H_2CO, ClO_2, NH_3, ClO, NO, NO_2, CO_2
Cryogenic emission spectrometer (under development)	Temperature, CCl_4, $CFCl_3$, CF_2Cl_2, $COCl_2$, COClF, COF_2, ClO, N_2O, HNO_3, NO, NO_2, O_3, H_2O, CH_4, CO
Far-IR emission spectrometer (under development)	HCl, HF, $CFCl_3$, CF_2Cl_2, CH_3Cl, ClO, $ClONO_2$, N_2O, HNO_3, N_2O_5, NO, NO_2, O_3, H_2O, H_2O_2, OH, CO, $O(^3P)$

The far-IR spectrometer also projects capability for measurement of HF, $CFCl_3$, CF_2Cl_2, and CH_3Cl in emission, so that it becomes the primary instrument for the measurement of these species. Should the remote measurement of $ClONO_2$, N_2O_5, H_2O_2, and HO_2 from a satellite platform become important, the far-IR instrument also promises capability for measurement of these species in emission.

It is quite possible, however, that a far-IR spectrometer may not mature in time for a first UARS mission. A particular difficulty is the long integration time required for measurement. The present projection is 30 s per observation, whereas the requirement is a maximum of 85 s for an entire altitude profile. Therefore, parallel development of new species-specific instruments should be undertaken to insure measurement of HCl, OH, and $O(^3P)$ in emission. The most important of these is OH in emission, if HCl is measured in occultation. As yet there is no projected method at all for measurement of CH_3CCl_3 and other industrial solvents. The occultation radiometer and laser heterodyne (occultation) radiometer provide back-up capability for HCl, HF, $CFCl_3$, CF_2Cl_2, CH_3Cl, $ClONO_2$, and H_2O_2, although the laser heterodyne capabilities are yet to be proven.

The microwave limb sounder assumes a primary role in Payload A for ClO, O_3 (meso), and winds (meso). A 1.27-μm radiometer provides a back-up measurement of mesospheric ozone, and a modulated gas cell radiometer might provide a back-up (or primary) measurement of mesospheric winds. The laser heterodyne radiometer provides backup capability in occultation for ClO. Development in the microwave region is necessary to realize the possibilities for measurement of OH and $O(^3P)$ in emission. Balloon test flights of a far-IR spectrometer, a laser heterodyne radiometer, and a microwave limb sounder are expected in the next year.

In addition to new instrument development, additional development of proven sensors might lead to improvements in sensitivity that more closely approach the desired coverage. An example would be cryogenic cooling of detectors and filters for increasing sensitivity. Scattered light and calibration accuracy are particular concerns for UV spectrometers.

The direct measurement of atmospheric wind fields, both in the stratosphere and mesosphere, is a very important area requiring development. The measurement of winds in the stratosphere and mesosphere is a necessary part of the UARS program. For questions concerning tides and tropical dynamics, accuracies on the order of 2 ms^{-1} with a spatial resolution of 2 × 250 × 500 km are desirable. The measurement of extratropical and tropical winds to high altitude, 15 to 120 km, is desirable. Various doppler methods for wind measurement in the IR and microwave spectral regions should be investigated.

The accurate measurement of vertical temperature profiles is an area in which refinement of the present technique is desirable. The accuracy and precision required is pushing the present state of the art. Studies should be undertaken to determine what are the precise requirements for the measurement and the limitations of various measurement techniques.

For measurement of H_2O, CH_4, N_2O, CO, and HNO_3, the capabilities of existing emission radiometers is adequate, but better accuracies (~5%) are desired and the altitude range should be improved. Pressure modulator radiometers would be required to decrease scan time to less than 85 s and to increase present height resolution (~10 km) for use on UARS. Measurement of CO and H_2O to 90 km would be desirable. The accurate (5%) measurement of mesospheric (50 to 100 km) ozone is a problem. Present emission radiometers are limited to measurement of ozone below ~70 km. Present occultation radiometers appear adequate for measurement of HCl, HF, and CF_2Cl_2. Concepts for measurements of $O(^1D)$, $N(^4S)$, and $N(^2D)$ would be desirable.

For measurement of NO_2, present filter radiometers do not have sufficient accuracy and are not capable of detecting NO_2 to adequate height. This could be improved, or a UV limb measurement might be used, such as on SME, where the accuracy is not yet known. For measurement of stratospheric NO, the pressure modulated gas cell radiometer is presently adequate. However, the requirement is stronger that this species be measured in the mesosphere. While no instrument has yet been built specifically for this measurement in emission, it appears feasible with present circularly variable filter radiometry technology or with anticipated advances in microwave technology to measure NO with 10% precision over the range 70 to 120 km. The solution for NO and NO_2 measurements requires filter radiometer instruments with increased cryogenic cooling.

To insure maximum information return from the UARS missions in a timely fashion, a supporting program of theoretical and laboratory work should be carried out in parallel with flight hardware development. The retrieval of vertical profiles of atmospheric constituents from spectroscopic and radiometric data requires an inversion procedure, and while the mathematical aspects of profile inversion are in general well developed, it is necessary that methods be formulated that are suitable for the needs of the mission and the particular measurement techniques being employed. In addition, a knowledge of the molecular absorption properties of the various species in appropriate spectral regions is required, and, in some cases, the ability to carry out line-by-line spectral synthesis may be needed. For many gases, absorption cross sections are not well known, and laboratory measurements along with supporting analyses are needed to achieve the level of understanding necessary for remote sensing applications.

Cryogenic cooling of instruments is another important area in which development is required. The mission lifetime, 18 months, is much longer than the 7-month lifetime of the cryogenically cooled instruments on Nimbus G. For this reason, the payload weights in Tables 5 and 6 are quite high for cooled instruments, and dewar sizes are much larger than for Nimbus G instruments. Cooling is required for the filter radiometer, NO emission radiometer, modulated gas cell radiometer, laser heterodyne spectrometer, far-IR spectrometer, and the cryogenic limb interferometer spectrometer. A summary of the UARS cooling requirements and possible systems is given in Table A-3. The systems outlined in this table do not exhaust the possibilities, but are representative feasible approaches. Further work is required to better define the systems and weights.

Table A-3. Summary of UARS cryogenic and cooling requirements and possible systems

Instrument	Temperature requirement	Possible cooling system	Estimated weight, kg		Power
			1 yr	2 yr	
Filter radiometer and NO emission radiometer	Detectors at 65 K	1. Solid cryogen	50	90	0
		2. Radiant cooler (if 95 K is acceptable)	Several kg		0
Far IR spectrometer	1.8–4 K detectors	Two stage Solid N_2/liquid He cooler	250	500	0
Occultation laser Spectrometer	20–80 K Detector	1. 80 K solid cryogen	50	90	0
		2. 20 K solid cryogen	90	180	0
		3. Radiant cooler (if 95 K is acceptable)	Several kg		
Cryogenic limb scanning interferometer/radiometer (10–15% duty cycle)	10 K detectors 30 K optics	1. Mechanical cooler for baffle and 100 K shield. Stored cryogen for optics/detectors	300	500	150-W cover open 50-W cover closed
	100 K telescope baffle	2. Totally stored cryogen system	500	900	
Pressure modulator radiometer	140 K detector	1. Radiant cooler	Several kg		0
		2. Solid cryogen	35	65	0