ATMOSPHERIC PHYSICS

Background

The advent of the Shuttle/Spacelab/Space Station era in the 1980's will provide unique opportunities for comprehensive studies of the atmosphere. Some progress has been made in understanding the Sun-Earth environmental system during the last decade, but major advances are needed before a working understanding of the basic behavior of our global weather system is obtained: the Sun-weather relationship, the role of anthropogenic constituents on the atmosphere, the coupling of the lower and upper atmosphere, to name a few examples.

The large weight-carrying capability of the early Shuttle/Spacelab missions will allow complex, large-aperture and long-focal-length remote sensing instruments to be carried aloft and to begin make-up global measurements of the type which cannot be carried out with the smaller free-flying satellites in use now. Cryogenic cooling systems can also be incorporated in the infrared instruments to give vastly improved signal-to-noise ratios. During the last couple of years, a large body of literature has been generated on the diverse and important scientific problems that such a Spacelab-borne instrument complement can address in the early to mid-1980's. The major limitation of Spacelab-based observations appears to be related to the limited flight duration. The availability of similar instrument complements on long-duration Space Station missions will result, for certain classes of problems, in significant enhancement in the scientific return over what is anticipated for Spacelab. Also, heavier and more elaborate payloads will be possible; larger telescopes, a more extensive complement of independent pointing controls, larger and more directive radio antennas, better cryogenics, and higher-power laser radar (lidar) transmitters are some of the possibilities presented.

Over the past several years, careful studies have been made of an optimum combination of atmospheric instrumentation for the Spacelab payload known as AMPS (Atmosphere, Magnetosphere and Plasmas in Space). Table 1 shows the proposed complement of instruments and the experiments for which they can be used in short-duration, low-Earth orbit.

Some of these instruments are described in more detail in the following subsections; however, a single example, that of the lidar, will illustrate the remote sensing concept. A downward-pointing tuneable dye laser can transmit pulses that are scattered resonantly from minor constituents such as neutral sodium (80-100 km) and ionized magnesium (100-150 km), giving both their global distribution and (by the use of high-resolution interferometry) the motion field of the lower thermosphere. Differential absorption of Rayleigh scattered UV pulses from the neutral atmosphere below 30 km, on the other hand, permits measurement of ozone and other absorbing constituents. This is just one of the instrument techniques planned for early Spacelab development that will be greatly enhanced by long-duration flight as a permanent space station.

TABLE 1. PROPOSED AMPS EXPERIMENTS

EXP. NO.	EXPERIMENTS	LIDAR	CRYOGENIC LIMB SCAN	FABRY-PEROT INTERFEROMETER	MICROWAVE LIMB SCAN	UV/VIS.	SUBSATELLITE CLUSTER, IN SITU	IR INTERFER., FAR	IR INTERFER., NEAR	SOLAR/STELLAR OCCULTATION	
1	MINOR CONSTITUENTS	X	X		X			X	X		LOW TO MEDIUM LATITUDES
2	CHEMICAL/DIFFUSION EQUIL.					X	X	X		X	
3	METEORIC MATERIAL	X	X		X	X			X	X	
4	D-REGION CHANGES	X	X	X	X	X		X			
10	TEMPERATURE (80-120 km)	X	X	X	X						
11	EDDY DIFFUSION	X	X	X	X			X		X	
12	COMP/WIND IN THERMOSPHERE			X		X	X			X	
14	ATMOSPHERIC TIDES	X	X	X		X			X	X	
15	IONOSPHERIC CURRENT SYSTEMS			X			X				
18	ATOM/MOLECULE PHYSICS	X		X		X			X		
8	ANOMALOUS/AURORA	X	X	X	X	X	X	X			POLAR
9	PARTICLES VS. O_3	X	X		X			X			
13	PART./JOULE HEAT			X			X				
16	PHYSIC. PROC./AURORA			X		X	X				
17	SOLAR/MAG./CLIMATE	X	X	X	X	X	X	X	X		
5	VIB. EXCITED OH	X	X		X				X		NEED DEVELOPMENT
6	OI VAR. (80-120 km)		X		X	X	X				
	NO. OF EXPERIMENTS	11	11	11	10	10	8	7	6	5	

Advantages of an STO

A polar orbit would be greatly preferred for the LEO station, but much useful information could be obtained from one of high inclination ($\sim 55°$). The completely new approach of a GEO station will open the door further for observations of the type which have been hitherto impossible, mainly in the area of hemispheric imaging. This global view of light scattered or emitted by minor atmospheric species will enable the dynamics of the entire global atmosphere system to be studied continuously, without orbital interruptions. The atmosphere can be monitored on its time scale and not that of the spacecraft. Sudden changes produced by events such as volcanic eruptions or stratospheric warmings may be reacted to quickly, as well as sudden outside events such as flares and substorms. Changes associated with the 27-day solar rotation may be readily observed in all meteorological parameters.

Observations of the Earth's limb from GEO will be possible at microwave frequencies, giving height profiles at all latitudes on the day and night sides. Scattered light from the Earth's disk will make ultraviolet and visible observations difficult on the limb due to the reduced angular distance between the Earth's surface and the limb region of interest. Development of a "tellurograph" (named by analogy with the solar coronagraph) would certainly make ultraviolet measurements possible, though the visible region is less certain.

The large variety of imagery possible from GEO argues very forcibly for the essential role to be played by a trained scientist in the Space Station, backed up, of course, by an extensive scientific team on the ground. Advantages in pointing and adjustment of instruments as well as the ability to make real-time decisions on how to respond to targets of opportunity were demonstrated in the solar program of Skylab to be real advantages of man's involvement. Further, it seems likely that a highly trained specialist would, in the course of a 3-month mission, gain competence and scientific insight through continued handling of new scientific data even more than a specialist located on the ground.

Moreover, a Solar-Terrestrial Observatory of the type envisioned here for the Space Station would lead to important and productive cross fertilization of the disciplines.

Program of Investigations

The atmospheric observations envisioned for the Space Station are all based on remote sensing using different portions of the electromagnetic spectrum; therefore, this section is organized along standard spectral divisions. Each subsection contains representative scientific problems and instrumentation to be used.

Ultraviolet Observations from the GEO Station.

a. Ozone. Global maps of ozone may be obtained using a telescope, an adjustable ultraviolet filter, and a digital camera for observing ultraviolet light scattered in the Earth's atmosphere. Ozone absorbs ultraviolet radiation between 2000 and 3000 Å. The absorption cross section is largest near 2550 Å and becomes smaller at longer and shorter wavelengths. An adjustable ultraviolet filter which would isolate portions of the spectrum between 2550 and 3000 Å would permit the measurement of ozone at different altitudes in the atmospheres. Using on-board data processing, a real-time display would show the global ozone distribution corrected for geometric factors. Using this display, the scientist-astronaut would compare variations in the global ozone with real-time displays of other atmospheric parameters such as the global temperature distribution at a particular pressure level or the global precipitation of charged particles into the atmosphere. He could then adjust the ultraviolet filter in order to display the ozone distribution at other altitude levels, thereby interactively following the evolution of ozone changes and the physical processes which cause these changes.

b. Charged particle precipitation. Charged particle precipitation in the Earth's atmosphere produces ultraviolet radiation. These same charged particles also produce odd-nitrogen (nitric oxide and atomic nitrogen) by bombarding molecular nitrogen and molecular oxygen. Global pictures of the ultraviolet auroral emissions are indicators of the global production of odd-nitrogen. Increases in the amount of odd-nitrogen in the mesosphere and stratosphere lead to decreases in the amount of ozone. The principal ultraviolet emissions from charged particle bombardment of the Earth's atmosphere are: the atomic oxygen line at 1304 Å, the atomic nitrogen lines at 1495 and 1745 Å, the molecular nitrogen Lyman-Birge-Hopfield bands between 1300 and 2000 Å, and the molecular nitrogen Birge-Hopfield bands shortward of 1100 Å. The spectral region between 1400 and 1700 Å is particularly well suited for measuring emission from charged particle bombardment since the atomic and molecular nitrogen emissions are optically thin. In this wavelength range, aurora may be observed on the daylight as well as the nightside of the Earth. Charged particle impact may be measured from geosynchronous orbit using a telescope, a broad-band UV filter, and a digital camera. A real-time display will enable the scientist-astronaut to correlate the occurrence of auroral precipitation with other atmospheric phenomena such as upper-atmosphere motions and ozone distribution.

Atmospheric Experiment Using the LEO station.

Photochemical reaction chamber. The concentration of ozone in the Earth's stratosphere and ionosphere is determined by a large number of photodissociation processes and chemical reactions involving highly reactive constituents such as atoms and excited species. In a recent National Academy of Sciences study some 93 processes were considered. In principle, each individual process may be measured in a laboratory experiment and the effect of all 93 processes may be taken into account using a model atmosphere calculation. In practice, many of the reaction rates remain uncertain because of the difficulty of handling reactive species in the confines of a laboratory apparatus. In addition, certain of the photodissociation rates remain uncertain because of screening by other atmospheric constituents. Again, the limitations of confined laboratory space prevent the duplication of upper-atmosphere densities and path lengths. Also, the details of the high-resolution solar spectrum are not available, in every case, for use in the laboratory.

A photochemical reaction chamber in low Earth orbit may be the solution to these difficulties. The unattenuated solar spectrum is available. A large reaction chamber may be fabricated from the expended external tanks of the shuttle. For studies duplicating reactions and photodissociation processes in the mesosphere and stratosphere, a window of fused silica will permit solar radiation longward of 1600 Å to enter the chamber. For studies duplicating photoionization processes in the thermosphere, a windowless entrance for the solar radiation and a flowing gas system will enable ionization reactions to be produced.

The photochemical reaction chamber should be instrumented with diagnostic equipment to determine the densities of the reacting species. The chamber may be used to measure individual reactions; or, since it will nearly duplicate the actual atmospheric environment, it may be used to test the interaction of a large number of constituents. This last feature would permit the testing of the effect of impurities on the Earth's stratosphere before the actual introduction of the impurity into the Earth's atmosphere.

Studies of the Visible Spectral Emissions from the Atmosphere. High-resolution spectroscopy in the visible region of the spectrum offers a number of rewarding experiments of the monitoring type as well as many possibilities for future developments. The major immediate goals for a long-lived space station mission would be the direct mapping of tropospheric and stratospheric winds inferred from Doppler shifts of absorption features in the spectrum of scattered sunlight. Wind speeds of a few meters per second can be obtained in this way, both at cloud tops and on the horizon. It should be noted that the cloud-top wind is the actual motion of cloud particles, not the apparent motion obtained by pattern motion studies.

In addition to these low-altitude parameters, one can monitor the mesopause wind and temperature from the OI (5577 Å) nightglow; the thermospheric winds and temperatures are easily obtained in the day and with somewhat reduced spatial resolution at night using OI (6300 and 5577 Å) line shapes and positions. During the day and over the auroral oval one can use the OII (7320 Å) ion line to determine large-scale ion temperature and drift speeds in the F-region, again from line shape and shift. This list is meant to be representative, not exhaustive.

The major instrumental requirement set by these spectral studies is high resolution, throughput, and stability. The use of a versatile Fabry-Perot interferometer with multiple etalons is clear. However, it may be possible to improve this complex by adding a single wide-angle Michaelson interferometer as the highest resolution element. This instrumentation will also form the basis of the high-resolution lidar studies. Here the major change would be the use of a controlled rather than natural source of excitation and scattering. This technique was discussed earlier in the introductory portion of this section.

It should be noted that there are significant differences in the studies that can be carried out from LEO and GEO. From GEO, horizon scanning in the troposphere and stratosphere will be difficult. However, the lack of relative motion will simplify the disk measurements and make possible the creation of a hemispheric "Dopplergram" showing atmospheric motions. The ability to watch the development of a particular dynamical event is clearly improved by observing from GEO. The lower-altitude polar orbit has a very significant advantage when altitude profiles are of primary importance.

Infrared Instrumentation. The role of infrared instrumentation on a space station is largely a continuation of an evolutionary process begun in the small, automated satellites. Vertical temperature profiles in the lower atmosphere, sea-surface temperatures, and cloud cover will continue to be important in terms of depicting the occurrence of various climatic situations.

To provide a real-time diagnostic temperature field for use in conjunction with man-directed experiments, some sort of basic vertical sounding capability should be included. A variety of instrument configurations would qualify for this application depending upon the vertical, horizontal, and time resolutions desired. In the case of pressure-modulated radiometers, this capability could be available for altitudes up to 90 km. GEO would allow hemispheric temperature fields to be obtained at selected pressure levels (vertically averaged) up to approximately 90 km. Thus, much could be learned about the role of waves with short time and space scales in the energetics of the upper stratosphere and mesosphere and the interaction of such modes with the geostrophic wind. Information about various components of the wind fields at low pressures should be available from the Doppler shift of lines.

The study of atmospheric composition should profit greatly from space station platforms. In the mid-1980's several techniques now under development should be available to improve the spectral resolution and sensitivity of infrared instruments. These include cryogenically cooled interferometers for use both in emission observations and solar-stellar occultations, laser-diode, and laser-heterodyne instruments. The long-duration missions implied in the space station concept will allow the necessary statistics to be gathered regarding the background concentrations of trace species and the magnitude of natural fluctuations both of short- and long-term nature. An important aspect of a manned involvement is maintaining the integrity of instrument performance and absolute calibration necessary to detect secular trends in the composition of the atmosphere due to pollutants.

Another new technique which may be available for monitoring the dispersion of man-made pollutants in the troposphere and their mixing into the stratosphere is correlation spectroscopy.

With sufficiently large telescopes, infrared limb sounding from GEO should be possible. This would allow nearly total latitude coverage at two local times on a nearly continuous basis but probably with a significantly lower vertical resolution than can be achieved in low Earth orbit.

Microwave Measurements. A manned space station, both LEO and GEO, will provide a unique platform for performing microwave (as used here, the term "microwave" also includes millimeter and submillimeter wavelengths) measurements of the Earth and its atmosphere which are relevant to improving our knowledge of solar-terrestrial relations and basic atmospheric processes. Short-term measurements which probably will have been performed previously from Shuttle sortie missions can be used to demonstrate the technique and answer certain questions, but important questions involving seasonal or longer variations and monitoring applications require a space station type platform. A GEO station can provide the first platform from which high-resolution microwave images and limb sounding can be performed; a manned space station is an appropriate platform for such measurements since a large ($\sim$ 25 m diameter) antenna is required and a trained operator could make real-time decisions concerning the mode of observation.

Microwave techniques can be used to measure profiles of atmospheric temperature, pressure, certain molecular species, winds, and the magnetic field over certain altitude ranges between the surface and lower thermosphere and with varying degrees of accuracy. They can also be used to map precipitation, sea-surface temperature, soil moisture, and possibly other parameters.

Prior to the availability of the Shuttle, it was not feasible to use limb sounding techniques in the microwave spectral region because of the large antenna required. With the advent of the Shuttle, however, such techniques are feasible. Table 2 summarizes theoretical results obtained to date on measurements which can be performed by such techniques with present technology. However, microwave radiometer technology is advancing rapidly and producing

TABLE 2. THEORETICAL RESULTS OBTAINED TO DATE ON ATMOSPHERIC PARAMETERS WHICH CAN BE MEASURED BY MICROWAVE OBSERVATIONS OF THERMAL EMISSION FROM THE ATMOSPHERIC LIMB

Parameter	Altitude Range (km)	Accuracy
Kinetic temperature	0 - 100	1 - 3 C
Pressure	35 - 70	1%
Winds	≤ 70 - 100	3 m/s
Magnetic field intensity	60 - 100	1%
O_2	90 - 120	*
O_3	15 - 90	*
H_2O	15 - 90	*
H_2O_2	25 - 50	*
ClO	30 - 45	*
CO	15 - 110	*
N_2O	15 - 50	*

*Meaningful accuracy is obtained over the indicated altitude range, given our present understanding of the atmosphere.

instruments with better sensitivity that are capable of operating at submillimeter and shorter wavelengths. The technology is anticipated to be sufficiently advanced by the time a space station is available that a much wider range of species than shown in Table 2 can be measured, including atomic O, OH, HO_2, NO, NO_2, HCl, and others.

The microwave measurements will be useful for improving our knowledge of atmospheric chemistry, energetics, and transport and will complement measurements which can be made in other spectral bands. An example of one problem of solar-terrestrial relations which microwaves can help solve concerns the energetics of the mesopause and lower thermosphere. The lower thermosphere is principally heated by the absorption of solar ultraviolet radiation by molecular oxygen. However, the temperature of this region is at its coldest near the summer pole, where there is continuous input of solar energy, and at its warmest near the winter pole, where there is no input of solar energy. Very substantial energy transport mechanisms must be operating to maintain such a temperature distribution. Knowledge of the spatial and temporal variations of relevant parameters in this region is far too scanty for quantitative modeling. The microwave measurements of kinetic temperature, O_2 variation, and winds in this region over a long time period should provide important inputs for understanding these mechanisms and how they respond to variations in solar parameters. Important complementary measurements in other spectral regions are also needed. For example, 15 μm emission to space by CO_2 is the major energy sink at the mesopause and should be monitored, as should the solar UV input. A space station could provide the first opportunity to perform such a wide range of interrelated measurements over a sufficiently long time period to determine patterns in the behavior of the parameters.

For LEO, an antenna of approximately 2 m diameter is required for microwave limb sounding. Such an antenna will provide vertical resolution of 3 km at the limb. It can also provide an order of magnitude improvement in resolution over that now planned in Nimbus experiments for images of sea-surface temperature and precipitation, both of which may be very important in studying solar-terrestrial relations.

For a GEO station, an antenna of approximately 25 m or greater diameter also capable of operating at millimeter wavelengths should be considered. With such an antenna, microwave limb sounding from geosynchronous altitudes is feasible. The antenna beam could be moved slowly around the limb as it is scanned in the vertical plane, giving latitude and altitude profiles of atmospheric parameters as a function of local solar time. The same antenna could be used in a conventional sounding mode to provide images or precipitation, water vapor, sea-surface temperatures, and atmospheric temperature profiles with horizontal resolution of ~25 to 100 km as needed by global circulation models. The antenna could also be used in an active mode for measuring atmospheric species of very low abundance. In this mode the antenna would either transmit, or receive from a ground station, radiation which is swept in frequency through a resonance of

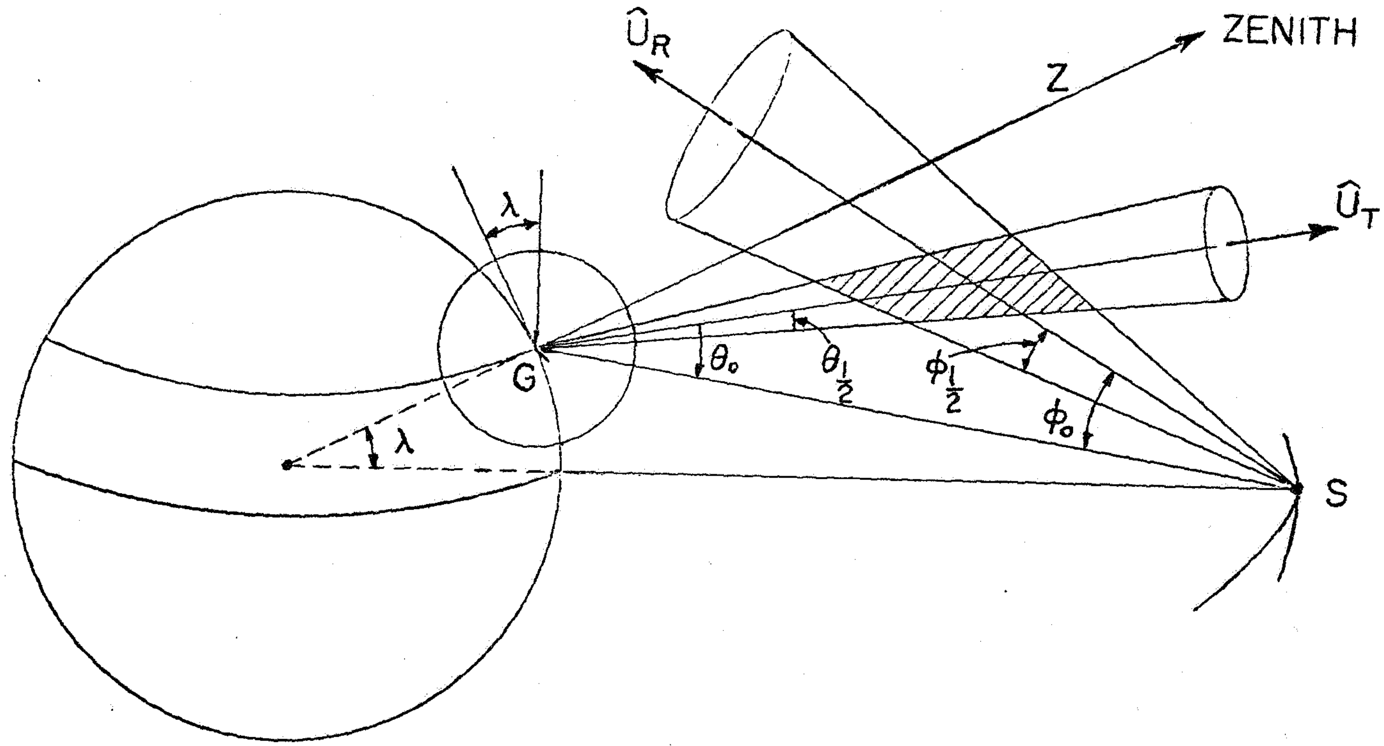

Figure 1. Spatial geometry of FISP system.

relative locations of the ground station G and space station S in the meridional plane. The transmitter beam of beam width $\theta_{\frac{1}{2}}$ points along $\hat{U}_T$, away from zenith Z, at an angle θ_o to axis GS. The transmitter beam of beam width $\phi_{\frac{1}{2}}$ points along $\hat{U}_R$ at an angle ϕ_o to GS. The scattering volume is shown by the shaded region. At small scattering angles (~ 3° or less), the plasma wavelength probed by the radio signal is greatly increased, and the scattered spectral width is narrowed, with a consequent enhancement in signal-to-noise ratio. The Debye-length limitation also disappears. Contamination due to the direct signal from the transmitter is minimized by pointing the boresight of the monopulse reviewing antenna at the transmitter.

Calculations show that a transmitting antenna and transmitter such as that at Arecibo, together with a receiving antenna on the GEO station, will comprise a FISP system with adequate sensitivity to probe the electron distribution and plasma wave spectrum within the plasmasphere. If plasma waves are present outside the plasmapause where nonthermal excitation gives them an intensity comparable to those in the plasmasphere, the FISP technique will be able to study them also.