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Chapter 4

Report from Ionospheric Science

Panel: W.J. Raitt, Chair; P.M. Banks, A.F. Nagy and C.R. Chappell

4.1 Introduction

The ionosphere is a region of the upper atmosphere in which the plasma population is dominated by thermal plasma with energies in the range 0.1 to 1 eV. It is commonly divided by altitude into regions delineated by slope changes in the altitude variation of the plasma density. In fact, these slope changes are related to changes in chemical and physical processes which occur at different altitudes giving rise to a nomenclature that describes the ionosphere in terms of D, E, F_1 and F_2 regions corresponding to increasing altitude from ~60 km to ~600 km. Above 600 km the thermal plasma still exists, but at mid and low latitudes it is dominated by light ions (H^+, He^+) and is sometimes referred to as the protonosphere.

Spatially the ionosphere can also be divided into two regions by latitude: the mid/low-latitude region bounded on average by the geomagnetic field shell with L=4, is called the plasmasphere, while poleward in each hemisphere is the region of the auroral/polar ionosphere. There is no clear altitude limit of the polar region as it merges into the magnetospheric tail. The two spatial regions are very different, the plasmasphere being characterized by quiescent thermal plasma while the polar ionosphere is dominated by a dynamic thermal plasma population.

Within the spatial boundaries of both regions referred to above, are a number of known features which have been observed by numerous techniques from both ground and space. These features together with the average altitude profile are summarized in Figure 4-1.

In the outline of ionospheric characteristics given above there have been references to average properties. This is an indication of yet another characteristic of the ionosphere; its temporal variability in both background characteristics and in the many features it exhibits. The time scale of the temporal changes varies from minutes in the polar ionosphere and hours for traveling ionospheric disturbances, to much longer diurnal, seasonal and solar cycle variations.

One clear message which stands out in this brief summary of the terrestrial ionosphere is that it is a complex region. Because of this complexity and high degree of variability in both space and time, we still do not understand the region well enough to predict its behavior accurately from time to time or place to place. The many years of ionospheric observations have given us a good qualitative picture of the ionosphere, but we are still a long way from an accurate quantitative model. However, in recent years the modeling of the ionosphere has moved ahead considerably to the extent that we are now lacking experimental observations to help quantify some aspects of the ionospheric models.

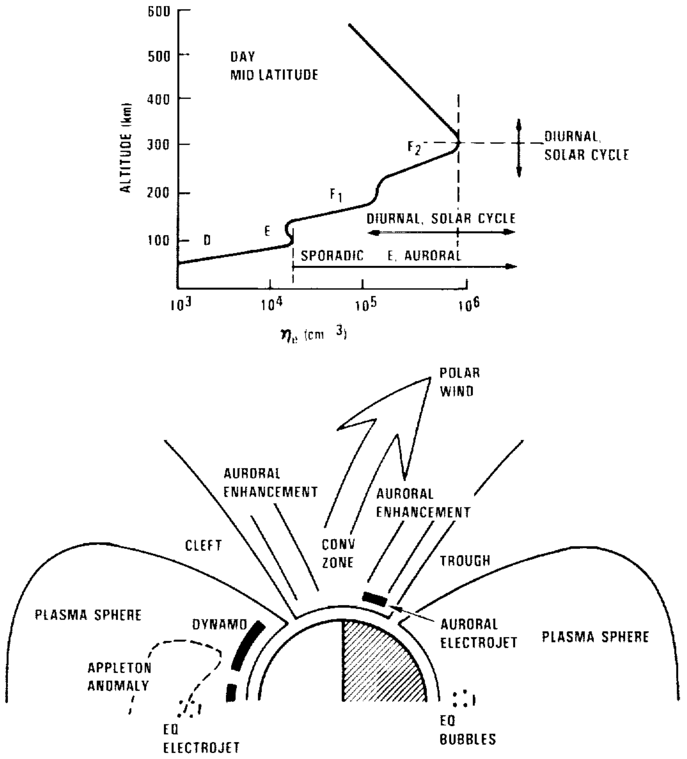

Figure 4-1. Some Known Ionospheric Characteristics

4.2 Importance of Ionospheric Studies

From its postulation in the early part of this century through its discovery in the 1930s until the present day, there has been continued interest in understanding the ionosphere. This interest ranges from the basic science involved in the formation and dynamics of the region through commercial and military interests involved with utilization of the ionosphere.

4.2.1 Basic Science

The ionosphere forms an interesting region in which plasma physics processes can be studied in an unbounded low pressure region of the upper atmosphere. The development of the steady-state ionosphere resulting from solar energy input and distribution as a result of a variety of physical processes has formed an ongoing interest for space plasma physicists.

4.2.2 Radio Wave Propagation

The ionosphere has an effect on radio wave propagation involving both reflection and transmission for frequencies which are below either the plasma frequency or the maximum usable frequencies, respectively. The characteristics of the ionosphere play an important role in the amount of energy that is reflected and therefore on the transmission characteristics of paths which utilize ionospheric reflection. This affects radio waves from the VLF to the very high frequency (VHF) ranges. As far as geosynchronous satellite communication is concerned, the transmission of data from the satellites is at a much higher frequency than the maximum plasma frequency encountered within the ionosphere, yet it is still affected by the ionosphere. The effect occurs in the very small changes in the transmission path at the S-band frequencies, often used for geosynchronous satellites which occur as a result of irregularities in ionospheric plasma density, particularly those close to the geomagnetic equator. These irregularities can result in small phase changes in the radio waves received on the ground, and this effectively sets an upper limit to the bit rate which can be used for transmission of data to and from geosynchronous satellites.

4.2.3 Atmospheric Interaction

The ionosphere plays a significant role in determining the properties of the neutral upper atmosphere. One of the ways in which it interacts is through ion drag effects whereby the plasma tends to remain attached to the geomagnetic field while the neutral gas is subject to forces which cause it to flow, resulting in collisions in which ions modify the flow of the neutral gas. The ion drag therefore affects both wind systems in the upper atmosphere and upper atmospheric waves. A consequence of the neutral atmosphere-ionospheric interaction force is to generate electric fields in the ionosphere resulting from charge separation as the plasma is forced to move relative to the geomagnetic field. These electric fields in turn can set up current systems which result in the atmospheric dynamo current system.

4.2.4 Magnetospheric Interaction

The ionosphere provides an impedance as a load for current systems which flow in the magnetosphere. Since the impedance for magnetospheric currents appears in the polar/auroral ionosphere it is subject to a great deal of variability resulting both from particle precipitation into the ionosphere and from the dynamic motion of the plasma in that region. In recent years it has been increasingly evident that the ionosphere also provides a source of plasma for the magnetosphere. Predictions suggested that light ions from the ionosphere could flow into the magnetosphere in the form of the so-called polar wind. More recently, studies of magnetospheric ion composition appear to indicate that there is a mechanism by which the heavier ionospheric ions, for example O^+, can reach the magnetosphere.

4.2.5 Noise Background

The presence of the ionosphere can provide a lower limit to the background noise of observations which are made through it. There is a continuous emission of optical fluxes resulting from ion chemical effects in the ionosphere. These are commonly referred to as the dayglow and the nightglow. In addition, in certain regions there is considerable radio noise background. This is particularly evident in the more dynamic polar regions of the ionosphere and is a result of plasma instabilities triggered by the variability of energy inputs into that region of the ionsophere.

4.3 Ionospheric Modeling

Ionospheric physics has made the transition from an exploratory phase to a degree of understanding in which predictability is a realistic goal. This capability will be provided by computer programs generally referred to as ionospheric models. In light of the importance of ionospheric studies described above, the models will play an important role in our understanding and utilization of the ionosphere as an important element of solar-terrestrial physics.

Ionospheric models provide a means of organizing and using ionospheric measurements for the wider community. The models give a predictive capability for global ionospheric properties as a function of geophysical parameters. Finally, they provide guidance on the type, frequency, and resolution required of ionospheric measuring systems which will be necessary to improve the validity of future models as they are developed.

At present, two general categories of models exist for describing ionospheric properties. Physics models, an example of which is the Utah State University Global Ionospheric Model (*Schunk,* 1988), and parametric models, an example of which is the International Reference Ionosphere (IRI) (*Rawer, et al,* 1981).

Physics models utilize a comprehensive description of the physical and chemical phenomena occurring within the ionosphere. As a result of this they place reliance on many measured coefficients describing plasma interactions, such as chemical rate coefficients and plasma collision frequencies. In order to predict the dynamic behavior of the plasma in the upper atmosphere, the models need to utilize magnetospheric particle fluxes and electric fields. At present these parameters are included on a somewhat arbitrary basis, because the linking of the particle and electric fields from the magnetosphere is not well established. In order to model the ionosphere on a global scale, using the techniques of numerical computation to solve the basic equations in the physical models of the ionosphere, massive computer resources are needed, and it is impractical to utilize such a model on a routine basis for a rapid prediction with a given set of input parameters.

Parametric models are based on taking a large amount of data and fitting a functional dependence of the measured ionospheric data, while taking into account a variety of measured geophysical parameters that have an effect on the ionospheric properties. The International Reference Ionosphere (IRI) provides a reasonable average description of the ionosphere, although comparison with specific measurements normally shows considerable deviation. The poorness of the fit is not uniformly distributed over the spatial and temporal domain. At low- and mid-latitudes a reasonably good description of the ionosphere is provided by the IRI, however, in the polar regions it is a long way from giving an accurate description.

In summary, the models provide a good guide to ionospheric properties but suffer in the physics case from inaccurate fundamental constants for some interactions and the very long time needed to calculate ionospheric parameters. The parametric models suffer from a lack of data in various regions of parameter space to the extent that, in the more dynamic regions of the ionosphere, they cannot provide a good description of the properties for all geophysical circumstances.

Although major advances have been made in our ionospheric modeling in recent years, it is becoming clear that the interaction of the ionosphere with the neutral atmosphere and the magnetosphere may not allow an independent model of the ionosphere to be used for predictions. The ultimate model of the Earth's upper atmospheric environment will eventually require a comprehensive atmosphere-ionosphere-magnetosphere model to adequately describe the region.

The ionospheric component of such a model, particularly at high latitudes or for small scale features at lower mid-latitudes, is dynamic enough that purely parametric models may not be a feasible solution. A hybrid model, which utilizes full physical descriptions but is organized to give rapid response to a given set of geophysical circumstances, may be necessary for providing accurate results on ionospheric properties with an adequate operational turnaround time.

4.4 Measurements Needed

4.4.1 Global Ionospheric Features

Some of the features of ionospheric models which require quantification are the spatial and temporal behavior of the ionosphere at various altitudes on a global scale. We are now in a position to predict this, but it is very difficult to utilize present or planned measurements to achieve an actual plasma distribution.

It is near or beyond the limits of technology to achieve this with the current height/space/time resolution of models. However, innovative imaging techniques are an area of instrument development that would greatly benefit ionospheric research in the future. By imaging we refer to the term in the most general sense including techniques other than optical imaging, both ground and space observation points, and the use of active imaging techniques.

In order to resolve the temporal and spatial behavior of larger-scale ionospheric features globally using optical techniques, the geosynchronous platform with maneuvering capability would be a good location for the instrumentation. However, polar cap measurements would not be well served by that location and an elliptical polar orbiting platform would be valuable in extending the observations of DE-1 and -2 and Viking, as well as providing coordinated observations from mid and low latitudes with the geosynchronous platform.

Other types of global imaging may require platforms nearer the ionosphere and could utilize radio wave techniques (ionosonde or incoherent scatter radar) or current sensing instruments to map out magnetic fields. If near-Earth orbits are used, the platforms should be in polar orbit to achieve global coverage, and multiple platforms would be advantageous to achieve some degree of global temporal resolution.

The value of any such imaging techniques would be greatly enhanced by coincident observations of solar flux (both photon and charged particle) from a solar observing platform situated outside the magnetosphere. In this way all aspects of solar variability in time and energy could be correlated to the global variation in the Earth's ionosphere.

4.4.2 Localized Ionospheric Features

Some aspects of ionospheric parameters are keyed to atmosphere, ionosphere and magnetosphere (AIM) coupling and involve small scale/rapid temporal changes which are less amenable to study by global imaging. Examples of such features would include small scale irregularities in density at both polar and equatorial latitudes, details of the convective flow pattern in the polar region and the ionospheric response to atmospheric gravity waves.

Our understanding of the ionosphere will be greatly improved if a systematic program of case studies is initiated to investigate these types of phenomena. Depending on the type of feature being studied, ground-based or any of a variety of space-based platforms could be used individually or in combination. However, as with global observations, the coincident measurement of solar input would immensely benefit the interpretation of the observations. Also, in the case of magnetospheric coupling effects, some coincident data on the configuration of the magnetosphere would be necessary.

4.4.3 Routine In-Situ Measurements

Global imaging will be biased largely to measuring the morphology of the ionospheric density characteristics, and, depending on the technique used, the accuracy of the observations would probably be less than that from in-situ measurements. Spatial resolution will also generally be lower. There is, therefore, a continuing need to gather background data on a variety of ionospheric parameters (plasma density, plasma temperature, plasma composition, and plasma flow) to extend the data base for coefficient determination used in parametric models of the ionosphere, and also to serve as a large collection of test data for physics models of the ionosphere.

A plan to routinely gather high quality in situ measurements over extended time periods should cover all geophysical conditions and last long enough to encompass at least one complete solar cycle.

Care in selection of instrumentation in terms of dynamic range and remote mode selection capability would enable the results to satisfy some aspects of the localized AIM coupling observations described above. Also, the flexibility of instrumentation is essential so that emphasis on a range of measurements can reflect the development of ionospheric models which the data is feeding.

In order to improve the predictive capability of ionospheric models, data collection and model development should proceed in parallel. This will prevent useful detailed measurements from being merely archived or compressed into a summary format.

4.4.4 Active Experiments

In the discussion of the utilization of ionospheric models it was pointed out that the physics models require a variety of coefficients describing basic physical and chemical processes involved in the formation and dynamic behavior of the ionosphere. Many of these measurements have been made in ground-based vacuum systems simulating the upper atmosphere, however, there is evidence that effects related to the dimensions of even the largest space simulation chambers can result in values of coefficients which are not applicable to the unbounded space environment.

In view of this, we believe it is important to institute a program to redetermine many of the key coefficients involved in ionospheric chemical and physical processes by controlled active experiments performed in the space environment. The large weight and power requirements of active experiments could be most readily accommodated on the space station, as long as contamination from the space station can be prevented from affecting the measurements. This type of experiment fits well into a concept of utilizing the space station as a spaceborne plasma laboratory in which the very careful, accurate measurements of interaction coefficients performed in ground-based facilities can be reproduced in the space environment.

4.5 Missions and Platforms

4.5.1 Present

Table 4-1 summarizes the requirements of an ionospheric component of a solar-terrestrial research strategy in terms of present resources

Table 4-1. Utilization of Existing Resources

			Unmanned Satellites				
Resource	**Ground Based**	**Sounding Rockets**	**DE**	**ISIS-2**	**HILAT**	**San Marco**	**Viking**
Global Ionospheric Features	M		M	M	M		M
Localized Ionospheric Features	H	H	H	H	H	M	H
Routine in-situ Measurements	M		M	H	H	L	M
Supporting Active Experiments	L	H					

H = High value
M = Moderate value
L = Low value
Blank = Not applicable

and programs. As indicated in the key, the various resources may have high (H), moderate (M), or low (L) applicability to the ionospheric studies, or they may be inapplicable.

Ground-based observations utilizing a variety of remote diagnostic devices are ongoing under funded programs. Because of the limited spatial extent of these facilities, even if networks are considered, they are of only moderate value in studying global ionospheric features. However, mobile or carefully located systems can be of great value in studying localized ionospheric features. Routine measurements are only moderately supported for the same reasons as the limitation on global measurements. However, if fixed site, local time behavior is needed, then a ground-based facility can be very valuable. Support of active experiments has a low level of applicability because the high energy required to be detectable on the ground precludes the rather precise, careful measurements of basic parameters being considered for supporting active experiments in this section. Ground-based resources are, however, valuable as remote diagnostics of active plasma studies performed in space.

Sounding rockets provide a valuable resource to the ionospheric community in their capability of providing short lead-time experiments to study localized phenomena, and to being suitable for certain categories of supporting active experiments. Clearly, the sounding rockets with LEO (low Earth orbit) altitude apogees are unsuitable for global imaging, and cost effectiveness would preclude using them for routine observations. An area in which sounding rockets will be of value is in the development of advanced instrumentation. The rocket payload would provide a useful low-cost method of obtaining initial space data as part of the planned development of a future operational instrument such as an innovative imaging system.

There are a few unmanned satellites which either are, or have the capability of, providing ionospheric measurements. DE, International Satellite for Ionospheric Studies (ISIS-2), High Latitude Satellite (HILAT), and Viking have moderate imaging applicability. The DE and Viking orbits and instrumentation favor polar and auroral imaging, but these are important aspects of ionospheric imaging and should provide very significant input for the future development of an optical imaging program. The ISIS-2 topside sounder represents a nonoptical category of imaging. It is classified as of moderate value because of the limited area viewed by the system, which requires extended periods of time to build up a global image. HILAT has similar limitations to DE, but is rather more restricted in imaging capabilities because of its lower orbit. The three polar orbiting satellites (DE, ISIS-2 and HILAT) all have the capability of contributing well to the study of localized ionospheric features and to the collection of routine in-situ measurements, although DE would be regarded as only moderate in the later aspect due to its high apogee. San Marco had a low inclination orbit and was therefore limited in the number of localized features accessible to it and in the extent of routine in-situ measurements. None of these relatively small unmanned vehicles is equipped to make supporting active experiments.

4.5.2 Planned

An assessment of future programs relevant to ionospheric studies, which are planned and funded, is provided in Table 4-2, using the same nomenclature for applicability as described above.

We assume that the ground-based and sounding rocket programs will continue and will support the same types of ionospheric studies described in the previous subsection.

There are several unmanned satellites in suitable orbits with appropriate instrumentation for investigations in future funded programs, two of which are NASA supported. The NASA ISTP polar satellite will provide similar ionospheric support to that described above for DE and Viking, however it will have the advantage of being part of a coordinated program with several other platforms providing important coincident stimulus and effect measurements. NASA is also developing the UARS program which, although primarily directed towards upper atmospheric studies, will include some in-situ ionospheric measurements to provide routine data measurements and studies of localized features.

Table 4-2. Utilization of Future Funded Programs

Resource	Ground Based	Sounding Rockets	Unmanned Satellites						Space Shuttle	
			EXOS-D	Cosmos Series	ISTP Polar	UARS	APEX	ACTIVE	ATLAS	TSS-1
Global Ionospheric Features	M		M	M	L	M			L	L
Localized Ionospheric Features	H	H	H	H	H	H			M	L
Routine in situ Measurements	M		H	H	M	H				
Supporting Active Experiments	L	H					H	H	H	H

H - High value
M - Moderate value
L - Low value
Blank - Not applicable

The Japanese Space Agency plans to launch EXOS-D in February 1989 carrying a complement of instruments to measure the characteristics of the terrestrial ionosphere. The planned orbital inclination of 75 degrees will result in a wide global coverage to provide valuable routine in-situ measurements, and will take the spacecraft to those locations where many of the localized features of the ionosphere can be studied. The in-situ observation will be supplemented by a television imaging system and an ionospheric sounder.

The extensive unmanned satellite program supported by the USSR offers the prospect of supporting a number of the ionospheric objectives in the near and more distant future. It is often difficult to get preliminary information on the payload composition of satellites in the Cosmos series. However, it is believed that these often carry plasma probes which have the potential of making them highly applicable to both the study of localized ionospheric features and routine in-situ measurements. Two other satellites planned by the USSR have had more prelaunch discussion than has been usual in the past. Apex is an unmanned payload planned for beam/environment interaction experiments, while Active will perform active wave experiments. It is not known how much passive observation these payloads will perform, but they will have high applicability to supporting experiments related to basic ionospheric physics.

There are two planned space shuttle experiments which will have some applicability to ionospheric studies. The ATLAS payload, due to fly in late 1990, will carry an imaging UV spectrometer (ISO) capable of making remote observations of ionospheric chemistry processes, an electron beam/plasma generator experiment (SEPAC) to perform active plasma experiments in the LEO environment, and an atmospheric emission photometric imager (AEPI) capable of supporting the active experiments. The TSS-1 payload is scheduled soon after ATLAS in early 1991. TSS-1 will carry some ambient plasma diagnostic instruments both on the Orbiter and on the deployed satellite. Its applicability to natural ionospheric studies is low because of the outgassing effects at the Orbiter end and, when the satellite is deployed, the high induced electromotive force (emf) in the conducting tether. In both cases the orbital inclination limitations imposed by a KSC launch restrict their usefulness for global studies, and the short duration precludes significant additions to a routine in-situ data base.

4.5.3 Future

As we look beyond planned missions to the more distant future, in which the existence of both man-tended platforms and permanently manned space stations becomes a reality, it is important to assess the value of these platforms and, if necessary, indicate how they will need to be supplemented by other space platforms to achieve the measurements necessary to have an ionospheric studies component in future solar-terrestrial observations. In order to successfully utilize the space station it will be necessary to have some resources and platforms available well ahead of the space station; in fact, in the very near future.

Table 4-3 summarizes the platform requirements in the near and more distant future. We anticipate ground-based and suborbital programs will continue and be utilized in much the same way as at present. However, with the greater load and power capabilities of a space station, it will be very important to have more readily available options to use high lift capability rockets to test some of the space station instruments before commiting them to that facility.

A new resource appearing in Table 4-3 is the existing ionospheric data bases acquired over most of the era of in-situ space science. Funded programs to revisit these data bases with our present and future capabilities in data handling and model interpretation would result in significant scientific value from a planned and adequately funded "mission to data."

The proposed small explorer class satellites will provide valuable platforms both for gathering data for model improvements and also for studying the characteristics of localized ionospheric features. Since these aspects of future ionospheric work are not well covered by space stations (except by use of tethered payloads) their utility could well go into the space station era by several years. The small size, low power, and restricted telemetry capacity limit the usefulness of these platforms in the areas of global imaging and active experiments.

Custom designed large satellites probably offer the optimum payload configuration for ionospheric measurements. Such platforms will enable imaging experiments to be placed in optimum orbits for resolution of ionospheric features, and they will also have the volume, power, and telemetry capabilities to group logically related instruments needed to study both stimulus and effect or, in other words, solar-terrestrial coupling effects. The value of these platforms to supporting active experiments in this area of study is rather more limited because of the removal of man from the loop.

Should a lunar base be established, then it would have considerable potential as a location to mount global imaging facilities. The distance may be too great for fine resolution of spatial/temporal effects in the ionosphere, but if techniques could be devised to image magnetospheric processes, then it would be well situated for those studies. There is some potential for performing active experiments at a lunar base. Since the

Table 4-3. Utilization of Planned and Proposed Future Resources, Ionospheric Programs Unfunded

Resource	Existing Data Bases	Ground-based	Sounding Rockets	Explorer Class Satellites	Large Satellites	STS	Lunar base	Space Station				
								Manned	Man Tended	Co-orb*	Polar	Tethered Payload
Global Ionospheric Features	M	M		M	H	L	H	L	L	L	M	M
Localized Ionospheric Features	H	H	H	H	H	L		L	M	M	H	H
Routine in-situ Measurements	H	M		H	H			L	M	M	H	H
Supporting Active Experiments	L	L	H	L	M	H		H	H	M	M	M

H - High value
M - Moderate value
L - Low value
Blank - Not applicable

*Co-orbital platforms

ambient environment has an extremely low pressure, it is possible to consider not only launching a controlled source of energy into the outside environment, but also to release material to simulate the upper atmospheric species, again under carefully controlled conditions.

The limited flight time, generally low orbital inclination, and contaminated environment of the STS reduce its value in carrying experiments to make global, local, or routine ionospheric measurements. The load carrying, power, and telemetry capabilities of STS do, however, provide it a role in performing active space plasma experiments which could be devised to support the basic ionospheric physics going into the computer models.

The space station heading includes several optional platforms associated with the NASA permanently manned facility. The manned space station suffers from many of the disadvantages of the STS in making ionospheric measurements, however, it is immersed in the space plasma and could conceivably be used to gather routine insitu data, albeit from a restricted latitude range. The man tended and co-orbiting platforms have similar restrictions to the manned facility except it is anticipated that the lack of life support systems will result in a cleaner environment for plasma measurements.

A polar platform is a more attractive option because of its global coverge and clean environment. Global features will be sampled on a daily basis, but imagery will be less well supported due to its expected low operational altitude. Active experiments will be somewhat less well supported than from manned systems because of the completely remote operation which would be required.

A final type of space station associated payloads will be tethered platforms. The utility of these payloads to support ionospheric measurements is improved over the manned structure because of the ability to deploy them out of the contamination region around the space station. However, orbital inclination and altitude limitations will restrict the coverage of the measurements. A further consideration in this technique is the electrodynamic effect associated with the conducting tethers. While this is of interest in its own right as active experiments, the electromagnetic fields associated with them have a possibility of intruding into the measuring region and affecting the ionospheric plasma measurements.

4.6 Summary

The general strategy to advance our knowledge of the ionospheric component of the solar terrestrial system should consist of a three-pronged attack on the problem.

Ionospheric models should be refined by utilization of existing and new data bases. The data generated in the future should emphasize spatial and temporal gradients and their relation to other events in the solar-terrestrial system. In addition, the time scale over which data is acquired should address the long-term solar-cycle effects and possible man-made pollution of the ionosphere. The goal of this aspect of the approach to ionospheric studies is the provision of an accurate predictive capability both for operational reasons and for utilization in basic studies of solar-terrestrial interactions.

In parallel with the improvement in modeling, it will be necessary to initiate a program of advanced instrument development. In particular, emphasis should be placed on the area of improved imaging techniques. The development of these techniques should not initially be tied to a definitive space mission, but should progress to that goal through an orderly development involving laboratory testing and spaceborne test flights to reach the stage of operational deployment of the instrument.

The third general activity to be supported should be active experiments related to a better understanding of the basic physics of interactions occurring in the ionospheric environment. The use of controlled energy fluxes in various forms in concert with local and remote diagnostic probes will enable naturally occurring interactions to be characterized over the wide dynamic range which occurs in the solar-terrestrial environment.

An important aspect of the implementation of the three-pronged attack is the logical