TECHNICAL ISSUES IN THE CONDUCT OF LARGE SPACE PLATFORM EXPERIMENTS IN PLASMA PHYSICS AND GEOPLASMA SCIENCES

Edward P. Szuszczewicz
Plasma Physics Division
Science Applications International Corporation
1710 Goodridge Drive
McLean, Virginia 22102

I. INTRODUCTION

Large, permanently-manned space platforms can provide exciting opportunities for discoveries in basic plasma and geoplasma sciences. The potential for these discoveries will depend very critically on the properties of the platform, its subsystems, and their abilities to fulfill a spectrum of scientific requirements. With this in mind, the planning of Space Station research initiatives and the development of attendant platform engineering should allow for the identification of critical science and technology issues that must be clarified far in advance of Space Station program implementation. An attempt is made here to contribute to that process, with a perspective that looks to the development of the Space Station as a permanently-manned "Spaceborne Ionospheric Weather Station". The development of this concept requires a synergism of science and technology which leads to several critical design issues. To explore the identification of these issues, the development of the concept of an "Ionospheric Weather Station" will necessarily touch upon a number of diverse areas, including:

1) System requirements and their hierarchy in experiment planning,
2) Ionospheric plasma physics and associated global-scale measurements and modeling,
3) Needs for tethered subsatellites,
4) Concerns with vehicle and tethered satellite interactions with the space environment, and
5) Scientific and engineering perspectives on the application of plasma contactors.

These issues, seemingly unrelated, are indeed synergistic, and bear on the planning for and application of the Space Station not only as an "Ionospheric Weather Station" but as a base for fundamental studies of plasma processes as they might be implemented by any number of active experiments (e.g., controlled injection of energetic particle beams). This overall synergism will be developed in subsequent sections, treating first the natural space station environment, the prediction and modeling of that environment, its consequences in terms of active and passive experiments, and its accessibility for comprehensive probing and attendant "Ionospheric Weather Forecasting". The treatment will establish a number of requirements, including a need for multiple-tethered subsatellites and environmental controls at the Space Station and at the location of the individual subsatellites. The requirement for environmental controls will concentrate on charge and current neutralization processes, and the applicability of plasma contactors.

II. A HIERARCHY OF ISSUES

Table 1 presents a hierarchy of technology issues that encompasses the planning of any spaceborne experiment. Issues at Level 1 address first-order requirements, including the fundamental subsystem support functions of power, thermal control, and information technology (e.g., data compression, storage, and transmission techniques). The focus here is not on these issues, but instead on "in-space operations", which at Level 2 converges on aspects of local scientific climatology, that is, on the sum total of prevailing conditions that affect the proper execution of the scientific mission. These concerns expand into Level 3 issues, with scientific attention to the availability of free-flying or tethered subsatellites, the natural, induced, and controlled space environment, and the platform's adaptability to scientific sensor requirements.

III. THE NATURAL ENVIRONMENT

With regard to the Station's natural geoplasma environment, reference is made to Figure 1, an illustration of the ionospheric plasma densities and associated phenomenological domains that would be encountered by the Station in a polar orbit at F-region altitudes. (A polar orbit is the desired configuration for an Ionospheric Weather Station.) Detailed discussions on each of the ionospheric domains can be found elsewhere (Szuszczewicz, 1986), while immediate purposes are served by a brief sketch of encountered conditions. The figure illustrates the broad range of plasma densities, including peak values near $2(10^6)$ cm^{-3} and minima near 10^4 cm^{-3}. (Minimum values can approach 10^3 cm^{-3}, depending on the altitude, season, and height of the F_2-peak.) The Figure also illustrates that the ionosphere can be substantially disturbed, with phenomena including broad-scale irregularity distributions (10's of kms to fractions of a meter) under nighttime conditions of equatorial spread-F (Singh and Szuszczewicz, 1984; Kelley et al., 1982). Similar irregularity distributions can be found at high latitudes on a nearly 24 hour-per-day basis (Singh et al., 1985; Rodriguez and Szuszczewicz, 1984; Ossakow et al., 1984). Only in the daytime hemisphere, at mid- and equatorial latitudes, can conditions be described as "quiescent".

The following points are of relevance to the Space Station and planned programs of research, engineering, and development:

1) Plasma densities can vary by three orders of magnitude on any given orbit, with the lowest density regimes of particular concern in dealing with the issue of spacecraft charging by natural energetic particle fluxes at high latitudes, by active beam injection experiments, or by $\vec{V} \times \vec{B}$ forces. (More detailed discussions on this issue will follow.)

2) The distribution of phenomenological domains offers limited periods of time for on-board experiments which require or assume near-constant ionospheric conditions. Near-constant conditions (in an orbit defined by upper F-region ephemerides) may not be available for periods extending beyond 15-20 minutes.

TABLE 1

HIERARCHY OF SPACE STATION PLASMA TECHNOLOGY ISSUES

LEVEL 1

- DYNAMICS AND CONTROL OF LARGE STRUCTURES
- FLUID MANAGEMENT
- ENERGY SYSTEMS AND THERMAL MANAGEMENT

- INFORMATION SYSTEMS
- AUTOMATION AND ROBOTICS
- IN-SPACE OPERATIONS

LEVEL 2: IN-SPACE OPERATIONS

- ADVANCED LIFE SUPPORT SYSTEMS
- ORBITAL TRANSFER VEHICLES

- PROPULSION
- MAINTENANCE AND REPAIR

- LOCAL SCIENTIFIC CLIMATOLOGY

LEVEL 3: LOCAL SCIENTIFIC CLIMATOLOGY

PREVAILING CONDITIONS AFFECTING AND/OR CONTRIBUTING TO THE SCIENTIFIC MISSION

- AVAILABILITY OF FREE-FLYING OR TETHERED SUBSATELLITES
- THE NATURAL, INDUCED, AND CONTROLLED SPACE ENVIRONMENTS
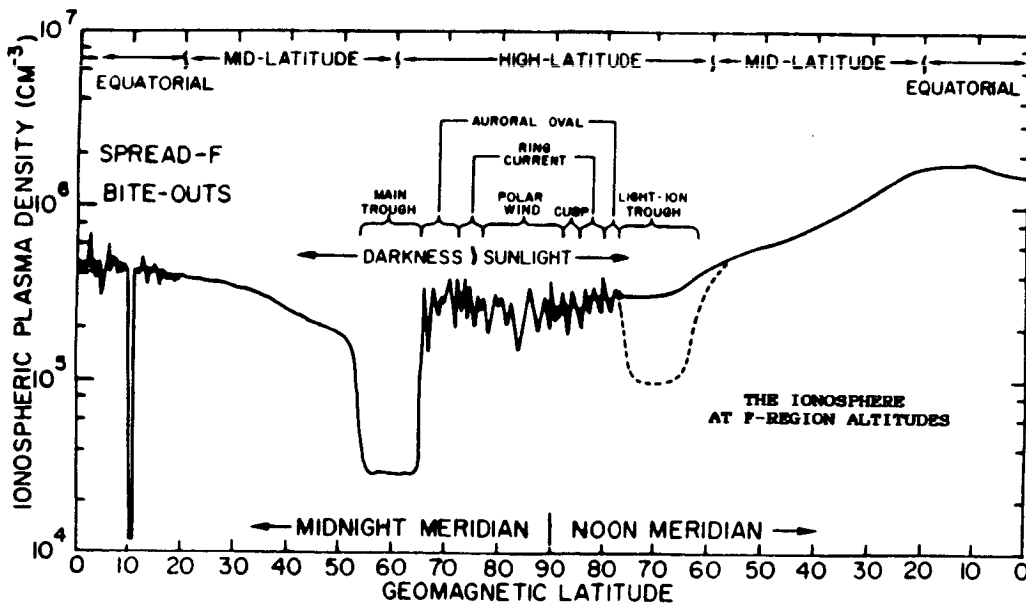- PLATFORM ADAPTABILITY TO SENSOR REQUIREMENTS

Figure 1. Phenomenological illustration of ionospheric F-region densities and irregularity domains in a noon-midnight meridian

3) The "average" F-region domain is relatively well understood, but not predictable on a day-to-day, hour-by-hour basis. For example, there is currently no genuinely predictive capability for the occurrence of equatorial spread-F, the location of the mid-latitude trough, the diffuse auroral boundary, or the specifics of particle precipitation events at high latitudes.

While the environment of the Space Station is not currently predictable in the truest sense, the Station's orbit parameters allow for its consideration as a permanently-manned solar-terrestrial monitoring system. Indeed, with certain technological accomplishments (to be discussed), the Space Station can be developed as an "Ionospheric Weather Station" with full capabilities to diagnose and predict the global-scale ionosphere. Such a capability would not only provide an important payoff in understanding the intricate role of the ionosphere in the solar-terrestrial system, but it would render a comprehensive description of the near-space environment applicable to ULF-EHF communications and remote sensing systems.

III. IONOSPHERIC PREDICTION

To predict the global-scale ionosphere means to state in advance the height profile of plasma density at any location at any time, and for any combination of solar, interplanetary, and magnetospheric conditions. In this sense, ionospheric prediction is a formidable goal, but one that the scientific community can legitimately aspire to in the year 2000 and beyond. Much work is already underway, with advances having been made in empirical and first-principles modeling. The empirical models (e.g., Rawer, 1981; Chiu, 1975) are seasonally-, monthly-, and hourly-averaged, with scientific intuition employed in the extrapolation of results to domains not covered by the available data base. Most empirical models use the sunspot number as an indicator of solar, interplanetary, and magnetospheric inputs to the overall ionospheric system, and on the average the model representation of the F_2-region (particularly peak densities) is good. This is illustrated in Figure 2 which presents a global IRI map of F_2-peak densities (that is, associated critical (plasma) frequencies) during solar maximum, near the autumnal equinox. (IRI is the empirically-derived International Reference Ionosphere of Rawer (1981)). The prescribed UT time is 0.0 hours and the month is October. The contours enclose contiguous regions of lower-limit plasma frequencies of the F_2-peak (defined as $f_0F_2 = 8.9(10^3)\sqrt{N_e(cm^{-3})}$. The IRI results are in agreement with averaged topside sounder measurements (Matuura, 1979; Schunk and Szuszczewicz, 1986), and included in the illustration are several intuitively satisfying features of the diurnal ionospheric behavior and its control by the geomagnetic field. These features include the sunrise enhancement of the peak density, its maximum towards the afternoon hours, and its relative position following the southward excursion of the dip equator across South America. (A brief editorial note of caution is added here to advise the reader of the inadequacies of the IRI (and other comparable global models) in its high-latitude prescription of density profiles. The averaging process tends to be dominated by photoionization, and not by particle precipitation events. Therein lies one of the more serious limitations of the IRI.)
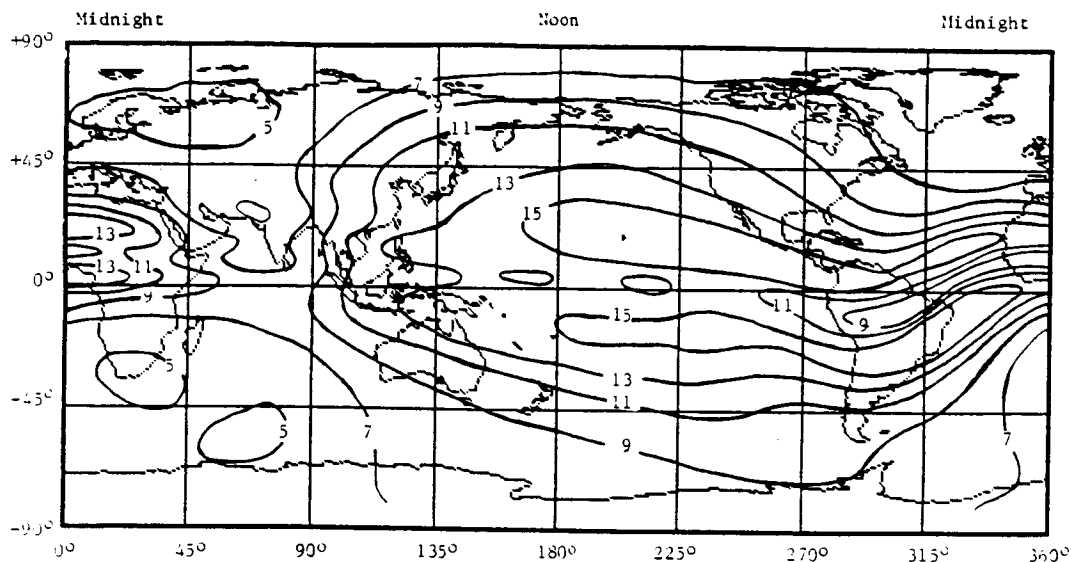
Figure 2. Boundary contours for minimum values of F_2-region critical frequencies, $f_0F_2 = 8.9(10^3)\sqrt{N_e[cm^{-3}]}$, as derived from the model International Reference Ionosphere, for sunspot maximum conditions (R=150) at UT = 0 hrs in October. The plotted units of f_0F_2 are MHz
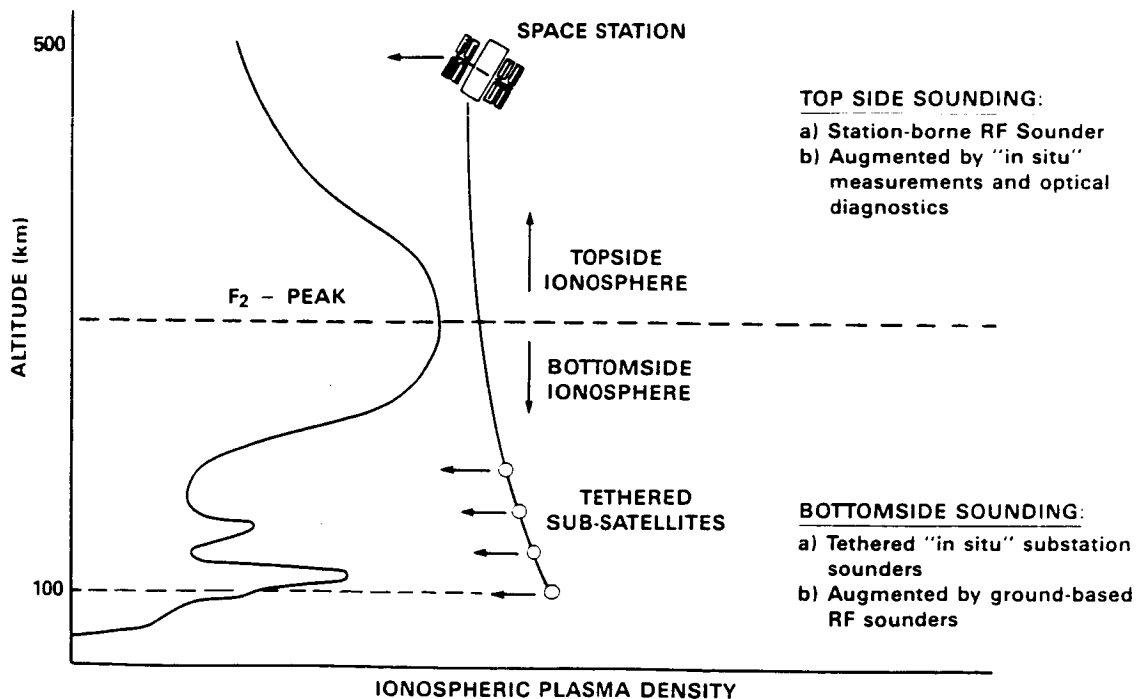
SPACE STATION

TOP SIDE SOUNDING:
a) Station-borne RF Sounder
b) Augmented by "in situ" measurements and optical diagnostics

TOPSIDE IONOSPHERE

F_2 – PEAK

BOTTOMSIDE IONOSPHERE

TETHERED SUB-SATELLITES

BOTTOMSIDE SOUNDING:
a) Tethered "in situ" substation sounders
b) Augmented by ground-based RF sounders

ALTITUDE (km)

IONOSPHERIC PLASMA DENSITY

Figure 3. Concept drawing of an ionospheric weather space station (see text)

229

The relative success in the IRI definition of world-wide f_0F_2 profiles is not matched in the E and F_1 domains where the data base is not as complete and synoptic, and the phenomenologies still represent a complex unravelled issue (see e.g., Szuszczewicz, et al., 1978). Available E and F_1 data are generally site-specific, largely because these regions have not been routinely accessible to orbiting spacecraft and associated synoptic data basing. This deficiency in E- and F_1-region data needs to be eliminated as a fundamental requirement of programs in ionospheric physics, solar-terrestrial relations, and communication sciences; and the requirement can be fulfilled if we look to tethered satellite technology and the development of a permanently-manned space platform as an Ionospheric Weather Station.

The problem of E- and F_1-region definition is not unique to empirical models, but is shared with the approaches of first-principle and semi-empirical codes (e.g., Sojka and Schunk 1984, 1985; Anderson, et al., 1985) Often, these codes do not include the E- and F_1-regions, a testimony to the complexity of the domains and the inadequate data base. This deficiency is acknowledged and is being worked upon; and the first-principles and empirical models are expected to make important advances in the upcoming solar cycle, with their participation in concerted campaign efforts that link model predictions with coordinated real-time observational programs. Two currently active programs are the National Science Foundation efforts called GISMO and SUNDIAL.

IV. THE WEATHER STATION CONCEPT

a. An Overview

Figure 3 presents a concepts drawing of an Ionospheric Weather Station that could provide the necessary diagnostics complement for simultaneous E-, F_1-, and F_2-region definition, networked into a worldwide ionospheric prediction service. The primary platform is the Space Station, in polar orbit at an altitude near 500 km, equipped with an on-board rf sounder for topside ionospheric profile specification between the F_2-peak and the station. The concept definition also requires that the station be equipped with a complement of "in situ" and optical diagnostics... particularly for the definition of high-latitude precipitation patterns, convection electric fields, and dynamics of the auroral oval.

The E and F_1 region data requirements would be satisfied with a tethered quadra-satellite configuration draped to a low altitude limit at 100 km, with each substation separated by approximately 10 km, and equipped with on-board measurement capabilities for plasma density, and ion and neutral composition.

b. Relevant Issues Involving Local Environmental Controls

The mission concept advanced in Figure 3 presents some very pressing technological issues... not the least of which is the difficult problem of tethering a single subsatellite (i.e., a substation) to the 100 km altitude (Baracat and Butner, 1986; Penzo, 1986). In addition, there are important local environmental issues at the main platform and its substations... issues that include gaseous effluents, electrical and magnetic contamination, and uncontrolled potentials and surfaces. We focus here on the issue of

uncontrolled potentials, and explore the associated implications of $\bar{V} \times \bar{B}$ effects.

Table 2 lists several simple formulae which address the quantitative aspects of uncontrolled potentials, charging levels, currents, and sheaths.

Tethering a substation to 100 km could present some threatening consequences. The application of equation 1a with (V, B, L) = (8 km/s, .25 gauss, 400 km) points to an 80 kV $\bar{V} \times \bar{B}$ potential difference between the main station and the subsatellite. Even potentials orders of magnitude lower present problems of limited ionospheric current neutralization, unusually large sheaths, and spacecraft safety.

An indication of sheath sizes can be attained with the use of Equation 3 (Szuszczewicz, 1983) and the listing in Table 2 of related results for ionospheric conditions corresponding to $1500°K$ and densities at 10^3 and 10^6 cm^{-3}. The wide variation in densities is directly related to the spread expected for the space station and its tethered satellites (see e.g., Figs 1 and 2). For a spacecraft potential of only 130 volts, the sheath size can approach 7 meters in the low density limit; and at 1300 volts it approaches 21 meters. These are undesirable limits that also threaten the application of energetic particle beam injection experiments from any space platform (Winkler, 1980; Szuszczewicz, 1985; and Papadopoulos and Szuszczewicz, 1986). This can be seen through applications of Equations 1b and 2 (Linson, 1982). Equation 1b points to the fundamental limit of ionospheric current flow to a spacecraft... nominally 1 ma of current to a 1 m^2 sphere with local plasma densities at 10^5 cm^{-3}. For an on-board experiment attempting to deliver a 1 ampere electron beam from a 1 meter spacecraft, Equation 2 would point to the most severe charging rate in the range of several kv/microsecond.

There has been a continuing effort to control the development of these large potentials and maintain the spacecraft at or near the local plasma potential. Some success has resulted from improved concerns with vehicle surface conductivities and expanded areas for current collection, but the magnitude of the problem has brought about a focus on the application of high-current on-board charged-particle sources, often referred to as "plasma contactors" (e.g., Krishnan et al., 1977; Lidsky et al., 1962; and Hastings, 1986).

c. Vehicle Current and Potential Control: Plasma Contactors

One type of plasma contactor is the hollow-cathode discharge, illustrated schematically in Figure 4. A thermionic electron emitter in the presence of a relatively high neutral gas flow, such a device can produce plasma densities upwards of 10^{14} cm^{-3} near the cathode orifice (Davis et al., 1986; McCoy, 1986; Wilbur, 1986). The expansion characteristics of this plasma (and its associated "contactor" capabilities) are influenced by specific device design considerations, the ambient plasma itself, and the local geomagnetic field. The ideal contactor should provide large controllable currents of electrons and ions at minimum applied fields in the cathode-anode region. Indeed, the technology seems to be moving in that direction (J. McCoy, private communication).

TABLE 2

VEHICLE CHARGING, CURRENTS AND SHEATHS

(1a) $\quad d\Phi[\text{volts}] = 10^2 \ (\vec{V}_{sc}[\text{km/s}] \times \vec{B}(G)] \cdot d\vec{L}(\text{km})$

(1b) $\quad I_\infty[\text{ma}] = \left[\dfrac{n_\infty \ [\text{cm}^{-3}]}{10^5}\right] \ \left[\dfrac{T_e[^\circ K]}{1600}\right]^{\frac{1}{2}} \ S[\text{m}^2]$

(2) $\quad \dfrac{d\Phi}{dt}\left[\dfrac{kV}{\mu s}\right] = 9 \ \dfrac{I[A]}{R_s[m]}$

(3) $\quad (R_{sh} - R_{sc}) = \lambda_D\left[2.5 - 1.54 \ \exp\left[\dfrac{-0.32R_{sc}}{\lambda_D}\right]\right] \ \left[\dfrac{e\phi_{sc}}{kT_e}\right]^{\frac{1}{2}}$

SHEATH SIZES

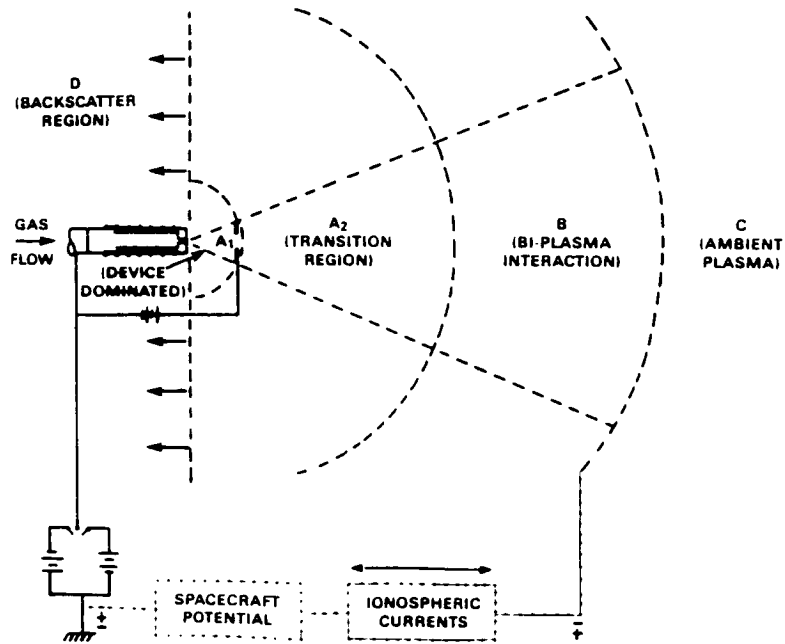| $e\phi_{sc}/kT_e$	Reasonable limits of probe theory			Substantial extrapolations of model		Plasma Conditions	
	1	10	10^2	10^3	10^4	$N_e[\text{cm}^{-3}]$	$T_e[^\circ K]$
$(R_{sh} - R_{sc})[m]$	0.21	0.67	2.1	6.7	21	10^3	1500
$(R_{sh} - R_{sc})[m]$	0.007	0.021	0.07	0.21	0.70	10^6	1500
$\phi_{sc}[\text{volts}]$	0.13	1.3	13	130	1300	...	1500

Figure 4. Phenomenological domains of hollow-cathode plasma interactions

While the bulk current-carrying characteristics of hollow-cathode contactors have been receiving attention, there is a need for the development of a detailed understanding of their intrinsic physical principles and the physics of the interactions with the local ionospheric plasma and the geomagnetic field. These interactions are critical to device performance and to the perturbations that the device are surely to introduce in the vehicle's near-space. The latter consideration bears on scientific requirements for cold-plasma-particle and wave measurements of the natural space environment. The science and technology of hollow-cathode contactor development must address this issue. Figure 4 presents a schematic view of the phenomenological domains of hollow-cathode operation in a space plasma environment. The cathode can be biased in either polarity with respect to the spacecraft ground and its outer skin (assumed a conductor in contact with the ambient geoplasma). The skin will itself be of either polarity relative to the local plasma potential, and appropriate ionospheric currents will flow across the spacecraft-associated sheath. The magnitude and polarity of this potential difference will depend on ambient plasma conditions, the spacecraft geometry and configuration, and the operation of on-board experiments (e.g. particle-beam injection). Another current path to the payload (besides that through the spacecraft sheath) is along and through the expanding hollow-cathode plasma. That expansion process, represented phenomenologically by regions A_1, A_2, B, and D, governs the current carrying capabilities of the hollow-cathode contactor.

The plasma production and expansion process begins with neutral gas flow into the cathode at relatively high pressures, typically in the range 1-100 torr. Plasma is created inside the thermionically-electron-emitting cathode and the neutral gas and plasma experience a choked flow as they pass through the cathode's exit orifice into domain A_1. In this phenomenological model, A_1 is defined as the "Device Dominated Region" because the attendant plasma processes depend crucially on the cathode characteristics and the anode-to-cathode fields. In zero order, the expansion of the neutrals in A_1 is thermal, while that of the charged particles is thermal with increasing drift velocities imparted by the applied field. The domain is collisional with orifice plasma and neutral densities quoted at 10^{15} and 10^{17} cm^{-3}, respectively (J. McCoy, private communication). The field in region A_1 can impart a relative drift velocity between the electrons and ions, with the electrons easily satisfying the Dricer field condition for the onset of collective plasma effects and the Buneman instability (see e.g., Davidson et al., 1970; Papadopoulos, 1977). This instability can turn on and off, heating the electron population, destroying all assumptions of isothermality, and affecting the plasma resistivity.

Exiting A_1, the source plasma can diminish to levels near 10^{12} cm^{-3} where it begins its exposure to a new electric field configuration resulting from the potential difference between the anode and the ambient plasma (beyond the sheath edge in region C). Region A_2 is dominated by the source plasma, which by current estimates should have a high kinetic β, excluding the ionospheric plasma and the geomagnetic field. A_2 is a transition region in which the source plasma diminishes in dominance over the domain and its kinetic β drops to unity. This is expected to occur over one-to-several meters, depending on prevailing conditions.

The processes in regions A_1 and A_2 may be considered less complex than those in region B, where counterstreaming source and ionospheric plasmas and magnetic field effects must be taken into account. In region B, the magnetic field controls the net electron emission or collection characteristics of the contactor, and it is here that the payload is truly in "contact" with the ionospheric plasma through the hollow-cathode discharge.

This discussion of plasma contactor operation is intended to expose the synergism of science and technology... for the ultimate current delivering capabilities and neutralizing effects on spacecraft potentials is dictated by the plasma expansion and counterstreaming phenomena in the varied phenomenological domains. While it appears justified to assume that hollow-cathode technology will advance to the point of large current and voltage neutralizing characteristics, the scientific requirements on any number of missions (including the Ionospheric Weather Station) will demand more from the characteristics of the hollow-cathode (or an alternate contactor design) than current or voltage neutralization. There are serious issues with the effects of the hollow-cathode on the local plasma, for the neutral gas flow is a contaminant in its own right and so will be the anticipated electrostatic noise characteristics of the device (e.g. Pirre and Berthelier, 1980). Application to beam-injection experiments is a case in point, where accumulating studies have discovered a broad spectrum of waves, ranging from 10's of Hertz to 10's of MHz. Continued studies would prefer no confusion introduced by the wave spectrum of a plasma contactor. A quality contactor (e.g. large currents and low electrostatic noise) could help immensely with continued e-beam experiments, and in the emerging era of neutral particle beams which carry their own energetic charged-particle components.

d. Contactor and Tether-Technologies, and the Ionospheric Weather Station

Should plasma contactor and tethered subsatellite technology make the appropriate advances, the Ionospheric Weather Station could become a reality. Configured as suggested in Figure 3, and adopting appropriately modified sensor techniques, the concept development would require 2 polar-orbiting space stations at an altitude of 500 km (or higher) in noon-midnight and 4 a.m. - 4 p.m. synchronous orbits. These stations would be equipped with particle and field detectors, auroral imagers, topside rf sounders, and tethered quadra-substations with "quiet" contactors and on-board measurement capabilities for plasma density and ion and neutral composition. The substation detectors would themselves require some developmental effort, in order to cope with pressure fields in the low-altitude drag regime. The comprehensive data set would then be networked into a global ionospheric prediction service which would archive the accumulating data base, test and validate first-principles and empirical codes, and extrapolate results in an ionospheric weather forecast mode.

V. REFERENCES

Anderson, D.N., M. Mendillo, B. Herriter, A semi-empirical, low-latitude ionospheric model, AFGL-TR-85-0254 (10 October 1985).

Baracat, W.A. and C.L. Butner, Tethers in space handbook, Bantam Books (1986).

Chiu, Y.T., An improved phenomenological model of ionospheric density, J. Atm. Terr. Phys., 37, 1563 (1975).

Davidson, R.C., N.A. Krall, and R. Shanny, Electron heating by electron-ion beam instabilities, Phys. Rev. Lett. 24, 579 (1970).

Davis, V.A., I. Katz, M.J. Mandell and D.E. Parks, Three-dimensional simulation of the operation of a hollow-cathode electron emitter on the shuttle orbiter, NASA/AIAA/PSN, Intl. Conf. on Tethers in Space (17-19 September 1986).

Hastings, D.E., The use of plasma contactors in the ionosphere, J. Spacecraft and Rockets (1986, submitted).

Kelley, M.C., R.C. Livingston, C.L. Rino, and R.T. Tsunoda, The vertical wavenumber spectrum of topside equatorial spread-F: estimates of backscatter levels and implications of a unified theory, J. Geophys. Res., 87, 5217 (1982).

Krishnan, M., R.G. Jahn, W.F. Von Jashowsky and K.E. Clark, Physical processes in hollow cathodes, AIAA J., 15, 1217 (1977).

Lidsky, L.M., S.D. Rothleder, D.J. Rose, S. Yoshikawa, C. Michelson, and R.J. Machin, Jr., Highly ionized hollow cathode discharge, J. Appl. Phys. 33, 2490, (1962).

Linson, L.M., in Artificial Particle Beams in Space Plasma Studies, B. Grandal, ed., Plenum Press (1982), p. 573.

Matuura, N., Atlas of ionospheric critical frquency (f_0F_2) obtained from ionosphere sounding satellite-b observation, RRL/Ministry of Posts and Telecommunications, Japan, March 1979.

McCoy, J., Electrodynamic interactions, in Applications of Tethers in Space, NASA Conf. Publ. 2422, NASA Scientific and Technical Information Branch, 1986.

Ossakow, S.L., E.P. Szuszczewicz, W. Burke, H.C. Carlson, P. Gary, R. Heelis, M. Keskinen, N. Maynard, C. Meng and J. Vickrey, Ch. 12 in Solar-Terrestrial Physics: D.M. Butler and K. Papadopoulos, editor NASA Reference Publication 1120 (1984).

Papadopoulos, K. and E. Szuszczewicz, Current understanding and injection in space, invited talk COSPAR, Toulouse (1986, to be published).

Papadopoulos, K., A review of anomalous resistivity for the ionosphere, Rev. Geophys. and Space Phys., 15, 113, (1977).

Penzo, P.A., A survey of tether applications to planetary exploration, NASA/AIAA/PSN, Intl. Conf. on Tethers in Space, (17-19 September 1986).

Pirre, M. and J.-J. Berthelier, Ion drift velocity measurements on the nose cone during the first Araks experiment, Ann. Geophys. 36, 389 (1980).

Rawer, K., International Reference Ionosphere - IRI 79, Rept. UAG-82, U.S. Dept. Commerce, November 1981.

Rodriguez, P. and E.P. Szuszczewicz, High-latitude irregularities in the lower F-Region: intensity and scale size distributions, J. Geophys. Res. 89, 5575 (1984).

Schunk, R. and E.P. Szuszczewicz, Global-scale empirical and first-principle models: a review and comparison with experimental results, (1986, in preparation).

Singh, M. and E.P. Szuszczewicz, Composite equatorial spread-F wave number spectra from medium to short wavelengths, J. Geophys. Res., 89, 2313 (1984).

Singh, M., P. Rodriguez, and E.P. Szuszczewicz, Spectral classification of medium-scale high latitude F-region plasma density irregularities, J. Geophys. Res. 90, 6525 (1985).

Sojka, J.J. and R.W. Schunk, A theoretical study of the global F-region for June solstice, solar maximum, and low magnetic activity, J. Geophys. Res., 90, 5285, (1985).

Sojka, J.J. and R.W. Schunk, A theoretical F-region study of ion compositional and temperature variations in response to magnetospheric storm inputs, J. Geophys. Res., 89, 2348 (1984).

Szuszczewicz, E.P., Controlled electron beam experiments in space and supporting laboratory experiments, J. Atm. Terr. Phys., 47, 1189 (1985).

Szuszczewicz, E.P., On the extrapolation of space simulation beam-plasma investigations to Shuttle-borne applications, AIAA J. 21, 1674 (1983).

Szuszczewicz, E.P., Theoretical and experimental aspects of ionospheric structure - a global perspective on dynamics and irregularities, Radio Science, 21, 351 (1986).

Szuszczewicz, E.P., J.C. Holmes, and D.N. Walker, Rocket observations of ionospheric E-region irregularities: implications for hf modeling, in Effects of the Ionosphere on Space and Terrestrial Systems, J.M. Goodman editor, U.S. Government Printing Office (1978).

Wilbur, P., Plasma contactor performance characterization, NASA Conf. Publ. 2422, NASA Scientific and Technical Information Branch, 1986.

Winckler, J.R., Electron beam experiments in space, Rev. Geophys. Space, 18, 659 (1980).