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LARGE STRUCTURES AND TETHERS WORKING GROUP

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I. INTRODUCTION

The Large Structures and Tethers Working Group sought to clarify the meaning of "large structures" and "tethers" as they related to space systems. "Large" was assumed to mean that the characteristic length of the structure was greater than one of such relevant plasma characteristics as ion gyroradius or debye length. Typically, anything greater than or equal to the Shuttle dimensions was considered "large." It was agreed that most large space systems and the tether could be better categorized as extended length, area, or volume structures. The key environmental interactions were then identified in terms of these three categories. In the following Working Group summary, these categories and the related interactions are defined in detail. The emphasis is on how increases in each of the three spatial dimensions uniquely determine the interactions with the near-Earth space environment. Interactions with the environments around the other planets and the solar wind were assumed to be similar or capable of being extrapolated from the near-Earth results. It should be remembered in the following that the effects on large systems do not just affect specific technologies but will quite likely impact whole missions. Finally, the possible effects of large systems on the plasma environment, although only briefly discussed, were felt to be of potentially great concern.

II. EXTENDED LENGTH

Structures for which one dimension is large relative to the plasma are best represented by the space tether although other systems could be envisioned. Examples include the Space Shuttle oriented with the nose-tail axis simultaneously along the magnetic field and velocity vector, such as sometimes occurs for polar orbits near the equator. In this case the wing axis is the large dimension – a narrow plasma beam before it has spread. Although both conducting and nonconducting structures were considered, the following discussion will focus on conducting structures, perhaps with a nonconducting surface to insulate them from the space plasma. For such structures, the primary interaction is the well known Lorentz force, which produces an induced electric field in the reference frame of the structure:

$$\bar{E} = \bar{v} \times \bar{B}$$

or

$$\bar{V} = \bar{E} \cdot \bar{L} = \bar{L} \cdot (\bar{v} \times \bar{B})$$

where:

E = induced electric field
V = induced potential drop
L = characteristic length of structure
v = velocity of vehicle
B = magnetic field

At Shuttle and Space Station altitudes, v is 7 to 8 km/s and B about .0.3 g so that typical potential drops are 0.3 V/m. As space tethers are expected to reach tens to hundreds of km, kilovolt or higher potentials are anticipated.

The existence of kV or greater potentials will lead to several key interaction issues. Chief among these for extended-length structures is the question of return currents where the plasma "contact" area may be only a few meters of conducting length on the two ends (large area and volume structures will have a similar problem but not, it is believed, nearly as severe as will the extended-length structures). Any application of the high voltages created in a conducting tether or similar extended-length structure will by necessity drive large return currents. It is anticipated that the ambient environment may not be able to directly support these currents so that any space systems wishing to draw power/current from the environment could be very inefficient. Plasma contactors are devices that have been proposed to eliminate this problem for extended-length systems by allowing efficient current collection from the ambient environment. Examples are electron beams, ion beams, neutral plasma generators, or large conducting spheres that could create artifically large current collection areas. The I-V curves of such devices at high potentials are not well characterized and represent a critical problem for the development of electrodynamic tethers. The consensus of the working group was that while in most areas of plasma interaction studies laboratory experiments were still timely and valuable, they have been essentially exhausted in this area and proper in-space experiments are critically needed.

The dynamics and stability of extended-length structures need to be carefully investigated. A specific concern in terms of the plasma environment are the electrodynamic torques and drag produced by the ambient plasma and fields. Whereas for most "normal" spacecraft, electrodynamic drag is small compared to neutral atmospheric drag, the large area-to-mass ratio of a tether will make it potentially sensitive to normally weak electrodynamic forces – although the cross section of a short segment is miniscule, the total cross section of a 100-km tether will be very large and is dependent on the details of the plasma interaction. (Note: in some applications, such as around Jupiter, it may actually be possible to draw electrical propulsion power from the tether, producing "antidrag"!) N. Stone has made a separate written contribution to the Working Group on tethers, which is included as an appendix.

III. AREA

"Large" area means that each dimension of the object's two-dimensional cross section is larger than the characteristic plasma dimensions. As an example, the cross sectional dimensions of a 1-m-diameter spacecraft are typically large compared to the electron gyroradius and the debye length – it is not compared to the ion gyroradius. In contrast, the Space Station cross section will be large compared with most plasma characteristic dimensions. Large solar arrays are another prime example of large-area structures.

The main concern with large-area interactions is the shadowing effect of the area. That is, the area will create a complex wake behind a surface in the direction of the velocity vector and, although primarily a three-dimensional structure, the wake will depend principally on the cross-sectional shape of the area normal to the velocity vector. Models currently exist, but more sophisticated models that incorporate magnetic field effects are lacking. In particular, in situ experiments and comparisons between in situ experiments and the models are desperately needed. Laboratory measurements have proven valuable but do not adequately address the relevant range of parameters and are generally limited in the $(Ro/Ld)^2$ ratios that can be measured (Ro=characteristic body length; Ld=debye length). In situ measurements are needed where Ro>>Ld (i.e., Ro>10^4 Ld). Measurements for both large conducting and nonconducting surfaces are necessary. Both laboratory and in situ experiments need to concentrate more on varying the surface potential in order to determine wake variations dependent on this critical parameter. For truly large area-to-mass structures (such as the Solar Sail, the Space Based Radar, and the Solar Power Satellite), the electrostatic drag and the pondermotive forces may become as important as the neutral atmospheric drag; few accurate models of these phenomena currently exist. Finally, the basic issue of how the plasma wake and magnetic field couple to produce the observed EMI needs to be carefully studied – such noise may set a lower limit on noise levels in the vicinity of large structures. The scaling law that relates the EMI to size is not known since measurements aboard the Orbiter are complicated by the introduction of large amounts of outgassing products.

IV. LARGE VOLUMES

Unlike extended-lengths and large areas, it is much more difficult to determine the scaling laws for large volumes. Here we assume that "large volume" encompasses the concept of the perturbed volume around a body. In particular, we include the interaction of the local gas cloud (as from emitted gases) surrounding a body with the plasma and ambient neutrals and the resulting modification of the local environment in the concept of large volume.

Key outstanding issues, in addition to the definition of scaling laws, are how plasma heating can take place (as is observed in the Shuttle ram) and how the heating scales with size and composition. Although studied as a function of area, the breakdown characteristics of high-voltage solar arrays have yet to be determined in terms of the perturbed volume at the surface of the arrays – in particular, the volumetric effects and differences between ac, dc, and pulsed power (as in the SDIO beam weapons) systems need to be considered. The dynamics of emitted fluids (liquid or gas) need to be investigated in terms of collective behavior. The so-called "critical Alfven ionization velocity" effect whereby reflected, high-velocity neutral particles in the ram direction self-ionize is another potential plasma interaction issue about which we know little. As locally generated magnetic fields of very high amplitude are being considered for various experiments, their effects on a large volume must be characterized. Models and in situ experiments to evaluate these effects need to be carried out hand in hand.

A potentially dangerous problem was identified as regards one very complex system that depends on volume – liquid droplet cooling. In these systems, millions of tiny droplets are emitted in order to eliminate heat. Because of their large area-to-mass ratio, they would be much more efficient at emitting radiation than current solid-surface emitters or cooling vanes. The interactions of such systems of concentrated macroparticles with the environment (for instance, gravity effects could be dominated by electromagnetic effects) over a large volume are virtually unknown. In the early days of the space program, one attempt at creating such a population of macroparticles using thousands of tiny metallic needles to create an artificial, radio-reflecting layer was actually successfully carried out. It is not clear what the differences between conducting or nonconducting droplets would be. Although the system is intended to be closed (the particles would be captured and recycled), the environmental impact of such a cloud if the particles were to escape is frightening considering the current state of affairs vis-a-vis space debris.

Although a concern for all three systems, the adequate measurement of the ambient and perturbed environment around and within a large volume will be potentially difficult and expensive. As local variations may be critical to an adequate understanding of the interaction of a large volume with the environment, it will be necessary to make many measurements simultaneously in time throughout the perturbed volume. To date, such measurements have been virtually impossible due to the expense of the many types of instruments required, the massive amounts of data that need to be correlated, and the shear difficulty of deployment. No easy answer currently exists for this problem although proliferation of cheap, simple, probe systems is currently being investigated. It is, however, more than likely that an entirely new technology, one encompassing measurment and analysis techniques, will be required before an adequate understanding of the interactions of large volumes with the environment will be possible.

V. SUMMARY

Table 1 summarizes the findings of the Large Structures and Tethers Working Group. Briefly, the key plasma technology issues have been defined in terms of large one-, two-, and three-dimensional systems. The addition of each spatial dimension compounds the potential plasma issues that need to be considered for successful missions in the year 2001 and beyond. The most critical issues are: (1) how will large, extended structures be grounded to the plasma environment? (2) what effects does the magnetic field have on wake shape and EMI for large areas? (3) how do large volumetric structures/environments respond to the ambient plasmas and fields? and, finally, (4) large structures may, by their very size, seriously impact the natural plasma environment – a plasma issue little studied in the past.

Table 1. Summary of Key Plasma Interactions for Large Space Structures and Tethers (see text for discussion of issues).

Spatial character	Key plasma issues
Extended length	$(\bar{V} \times \bar{B}) \cdot \bar{L}$
	Plasma contact (grounding)
	Current loop closure for conducting tethers
Large area	Wake structure
	Magnetic field effects
	Electromagnetic noise turbulence
	Electrostatic drag
	Variable surface potentials
	Pondermotive forces and effects on system dynamics
Large volume	Effects of emitted fluids (gases and liquids)
	Macroparticle assemblies
	High-voltage breakdown
	Plasma heating in the ram
General	Simultaneous measurements in three dimensions
	Scaling laws with size, magnetic field, and particle environment

APPENDIX I.

Comments by

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The use of a tethered satellite system to place an instrument package into a low-altitude orbit to map out the plasma characteristics, currents, winds, and in the lower thermosphere (i.e., altitudes in the range of 100 km) will require several extensions of existing technological capabilities. The following are examples:

(1) The presently designed NASA TSS is capable of deploying a satellite to a maximum of 100 km on a nonconducting tether. The Space Station will orbit at altitudes in the range of 350 to 500 km. Therefore, (i) a deployment system must be developed that can handle up to 400 km of tether. (ii) The dynamics of tether, once established by the TSS-1 and TSS-2 missions, should be reassessed to include very long tethers of the required length. A modification to the control system may be required.

(2) Tether degradation should be studied in more detail (this will be more important for long-duration Space Station tethers than the 4- to 7- day TSS missions). This includes, for example, micrometeorite strikes and atomic oxygen erosion.

(3) Tether and tethered satellite thermal control will be a critical issue for altitudes below 125 km. At 90 to 100 km (the most interesting range because of the turbopause), heating will be a significant problem and active thermal control techniques (such as phase change materials) will be required.

(4) Satellite aerodynamics/plasmadynamics will also be important at 90 to 130 km altitudes. The shape of the satellite and the location of instruments will be critical.

(5) Tethered system dynamic noise and its possible interference with experiments as well as other Space Station activities (in particular, microgravity experiments) will be important. Avoidance and/or control of dynamic noise will require careful evaluation of the theory and of data obtained from the TSS-1 and TSS-2 missions