# Outer Atmospheric Research Using Tethered Systems

John L. Anderson*
*NASA Headquarters, Washington, D.C.*

**The region about 90–150 km above the Earth is a major part of the upper or outer atmosphere. It is relatively unexplored, being too high for balloons or aircraft and too low for persistent orbiting spacecraft. However, the concept of a tethered subsatellite, deployed downward from an orbiting, more massive craft such as the Space Shuttle, opens the possibility of a research capability that could provide global mapping of this region. The need for research in this thick spherical shell above the Earth falls into two major categories: 1) scientific data for understanding and modeling the global atmosphere and thereby determining its role in the Earth system and 2) engineering data for the design of future aerospace vehicles that will operate there. This paper presents an overview and synthesis of the currently perceived research needs and the state-of-the-art of the proposed tethered research capability.**

## Introduction

ON a clear day, the atmosphere is not nearly as simple as it looks. Its varying, multilayered structure is complex, as are its physical, chemical, and dynamic processes. For all the Earth's land and ocean wealth, it is the cocoon of atmosphere around it that protects and even regulates life here. The lower part is understood somewhat—we breathe it and fly in it, our weather is manufactured in it, and it is critical to our ecosystem. Although little is known of its upper or outer part, what happens there in the ionosphere and thermosphere transmits its effects deep into the lower atmosphere, even down to the Earth's surface.

The region above the Earth, known as the upper or outer atmosphere, extends from about 90 km up to where space begins, perhaps to 220 km where the Shuttle can typically orbit. Research instruments have not spent much time there—it is too high for balloons or aircraft and too low for persistent orbiting spacecraft. In fact, this region has been called the "ignorosphere" by atmospheric scientists. The meager research data about this region have come from sounding rockets, spacecraft with highly elliptic orbits, and the transiting Shuttle Orbiter. However, the concept of a tethered subsatellite, deployed downward for perhaps 100 km from the orbiting Shuttle, opens the possibility of a research capability that could provide global mapping of this region.

This paper presents a synthesis of the currently perceived needs for such research merged with an assessment of a possible research capability for that region. Several major roles that the outer atmosphere plays in Earth system processes and human operations have been collected and synopsized. The potential tethered research capability is presented by describing the particular research interests, experiment concept, technology state-of-the-art, and proposed plans for such a tethered system.

## Outer Atmosphere

If the outer atmosphere is compared to the lower or even middle atmosphere below 90 km, it may seem barren, remote, and uninteresting. The lower atmosphere with its easily seen richness and diversity—clouds, storms, and flight—appears far more important. But that obvious and easy comparison is misleading. It diverts attention from the less evident processes and characteristics of the outer atmosphere, which, we are learning, possibly may be equally significant.

There is evidence to support this. "Although space as viewed from the Shuttle appears to be empty, the atmosphere extends beyond the low-Earth orbital altitudes but it is so thin that only very sensitive instruments can detect it. Its effects are noticed in the gradual decay of satellite orbits, and faint lights emitted in the upper atmosphere."[1] Even in this very thin air, wind patterns and temperature distributions exist.

Two Dynamics Explorer (DE) satellites launched in 1981 (DE-1 was still operational in 1988) discovered dramatic interactions between the Earth's ionosphere and magnetosphere.[2] The DE polar orbits have had perigees of about 560 km (DE-1) and 300 km (DE-2). So they have examined the environment that forms the enveloping boundary of the outer atmospheric zone.

Interestingly, the outer atmosphere assumes a greater stature if it is approached from the outside, that is, from deep space. Imagine a space journey in which you finally arrive in the vicinity of the Earth. You have traversed deep and solar space and are now encountering the exosphere of a blue-and-white planet. Your instruments are far advanced. They alert you to a complex new pattern of "weather" in space. The solar wind and galactic radiation are engaging the Earth's magnetic field in a spectacular display of light; if beings exist on the planet below, they must be able to see these polar auroras at night. Solar energy and matter are being deposited in this outer atmospheric zone. Electromagnetic radiation is being selectively absorbed. Your instruments sense the beginnings of atmospheric chemistry. At some point a dramatic discovery is made—this zone has been a transition from the tenuous plasma of space to a life-supporting atmosphere. It is the only such transition zone known to the beings on the planet. That in itself makes it both interesting and important to them.

### Dynamic Activities

A graphical summary of the dynamic activities of the outer atmosphere is shown in Fig. 1. Even this simplified illustration indicates the great complexity, interactivity, and dynamism of the outer atmosphere. Four columnar slices through the outer atmosphere are shown to deal with separate physical properties: thermal, chemical, mass dynamics, and electrodynamics. A fifth column provides a comparative look at human opera-

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*Program Manager, Tethered Systems Technology, Office of Aeronautics and Space Technology.

tions in this region. In terms of vertical orientation, the zone from about 90 to 110 km performs the coupling between substantially differing properties of the atmosphere above and below.

The outer zones just below space and just above the clouds are filled with activity: waves in very thin air far above the highest clouds, storms of charged particles, vertical tides of air, large rivers of electric current generated by wind-dynamo effects, and a "cold" layer sandwiched in where it does not seem to belong. What happens there affects many of the Earth's processes, which in turn affect both our habitat and our ecology. This is also the region where hypersonic vehicles of the future must go.

Not nearly enough is known about the outer atmosphere to create mathematical models of its overall interactive behavior.

> The development of improved models of the outer atmosphere would be of great benefit to a number of problems relating to orbital dynamics and to the space environment overall. It would also contribute significantly to our understanding of solar-terrestrial relations, with specific applications to the problems of communications and power-transmission failures in connection with geomagnetic storm events and to questions of the possible influence of solar activity in regard to weather on the Earth's surface.[3]

### Earth Systems

The constituent activities of the outer atmosphere shown in Fig. 1 combine to fulfill several roles in the Earth system and in human endeavors. This section synopsizes the following roles:

1) Energy interaction zone for space radiation, solar wind, and Earth's magnetosphere.
2) Transition zone between space and life-harboring atmosphere.
3) Protective radiation shield for Earth's life forms.
4) Local example of magnetized plasmas present in universe.
5) Solar energy input manifold for atmospheric "heat and electrical engines."
6) Restrictive filter for ground-based astronomy.
7) Regulator of high-frequency radio communications.
8) Operational zone for future aerospace craft.

"For millennia we have based our views of the universe on observations in the narrow visual octave of the electromagnetic spectrum, 400–800 nm, supplemented during the last half century by infrared and radio observations. During the last decade, however, space research has opened the full spectrum..." The x-ray and gamma-ray regions are of special importance and they form a picture of the universe called the plasma universe that is often drastically different from the traditional visual universe.

> As the universe consists almost entirely of plasma, our understanding of astrophysical phenomena depends critically on our understanding of how matter behaves in the plasma state. In situ observations in near-Earth cosmic plasmas offer an excellent opportunity for gaining such an understanding. Near-Earth plasma covers not only vast ranges of density and temperature but also a rich variety of complex plasma-physical processes.[4]

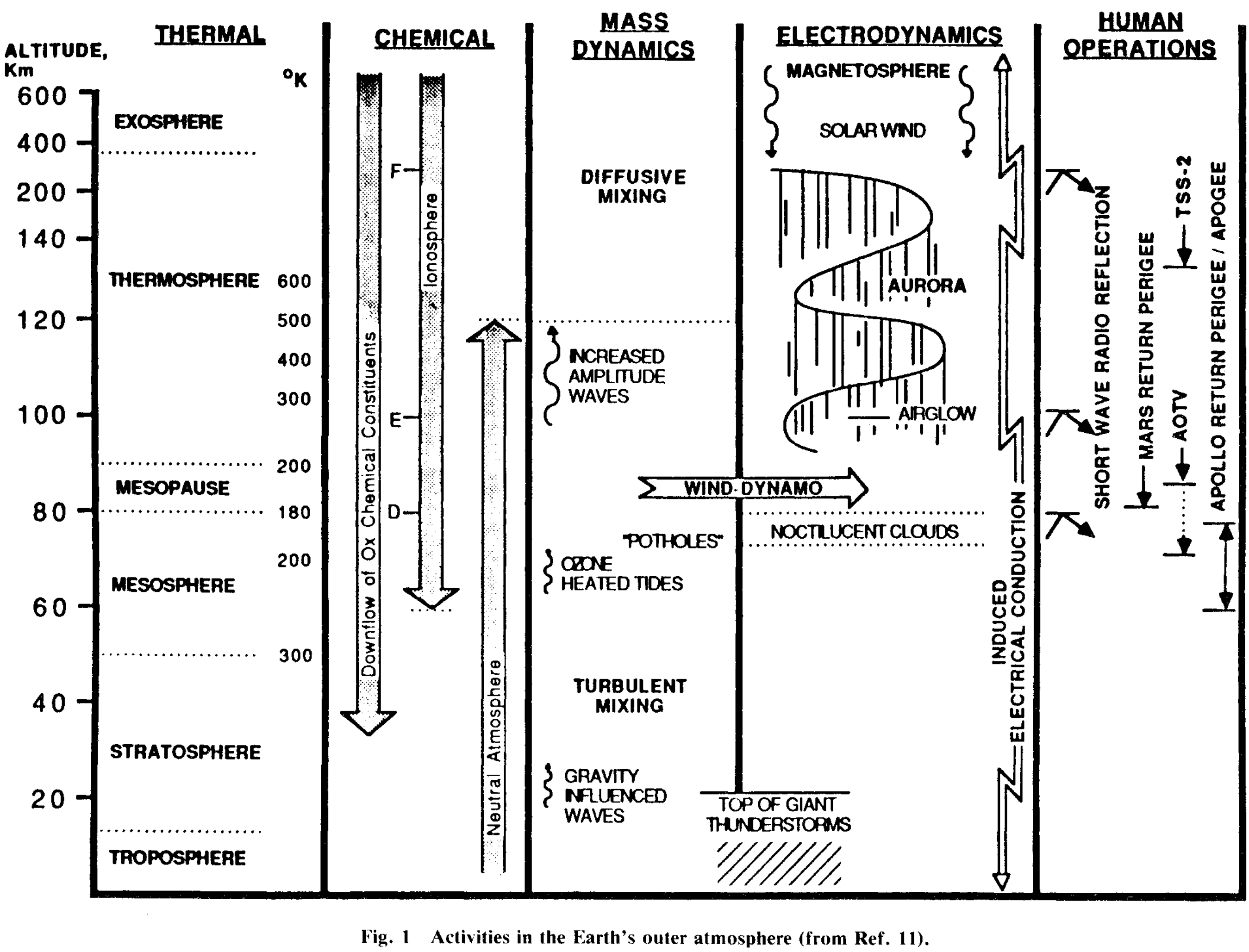


Fig. 1 Activities in the Earth's outer atmosphere (from Ref. 11).

"The DE program found that the Earth's ionosphere supplies significant quantities of plasma to the magnetosphere, which in turn supplies large quantities of electrified gases (plasma) to space; that there may be a natural laser generating more noise than dozens of radio stations; and that the atmosphere at the edge of space has its own weather."[2] The solar-terrestrial plasma environment is especially relevant to our technological society because of its impact on communications, power transmission, long-term weather effects, defense systems, and various aspects of basic energy production and transport.

The outer atmosphere is the outer edge of the gaseous boundary between deep space and a planet with life. One vital function is as a protective shield for Earth's life forms, preventing lethal radiation intensity, particularly ultraviolet, from reaching the Earth's surface. As Fig. 2 (derived from Ref. 4) shows, most of it is absorbed in the outer atmosphere. Apart from scientific interest, concerns about the "ozone-depleted hole" found over the Antarctic stem from the resultant permitted increase in uv radiation. It should also be noted that the atmosphere permits life-supporting energy to reach the Earth's surface, e.g., for photosynthesis. Our life forms thus partially result because it is a highly selective filter.

Of course, the absorption of radiation causes energy to be deposited. Thus, the outer atmosphere becomes an energy input manifold for the thermal and mass "engines" of the atmospheric portion of the Earth system. Furthermore, the magnetosphere interacts to control the energy deposition from charged particles from the sun.

Another dynamic factor affecting the Earth system has emerged in the last few decades—human influences on the atmosphere. Possible global climate change might be caused by pollutant transport such as an increase in radiatively active gases (e.g., carbon dioxide, methane, chlorofluorocarbons, nitrous oxide, and tropospheric ozone). In one extreme, fortunately conceptual, case a "nuclear winter" with the Earth covered by resultant dark smoke would represent a catastrophic imposition on the atmosphere.

A recent perspective on the importance of understanding the global Earth system includes a definition and evaluation of major potential U.S. space initiatives.[5] Although Ref. 5 does not address tethers or outer atmospheric research specifically, it recommends a major coordinated international effort called Mission to Planet Earth. The goal of this initiative would be to obtain a comprehensive scientific understanding of the entire Earth system, by describing how its various components function, how they interact, and how they may be expected to evolve on all time scales. A broad program to develop a much greater understanding of the entire Earth system has been described.[6,7]

### Human Endeavor

From the perspective of ground-based human endeavor, the outer atmosphere plays several roles. In astronomy, it filters out some of the gamma ray, much of the x-ray, and nearly all of the ultraviolet radiation. It acts as an enveloping opaque shell that permits us to look at the universe only through very narrow slits corresponding to thin bands of the electromagnetic spectrum. In fact, the loss of information because of this filtering is so severe that four "great observatories" are being planned to operate in orbit outside of the atmosphere, at gamma ray, x-ray, visible and ultraviolet, and infrared wavelengths. However, such enormous attenuation and absorption of electromagnetic radiation in the outer atmosphere could yield significant insights about its properties—if research instruments could be placed there.

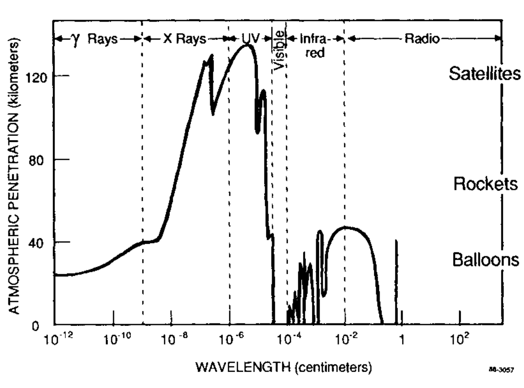


Fig. 2 Atmospheric absorption of spectral radiation (from Ref. 4).

In communications for most of the 20th century, long distance, Earth-based radio has used the reflective and even channeling properties of ionospheric layers. A capability for research at the 100 km layer, when added to that available at the 300 km layer, could provide unusual comparative information on electromagnetic radiation interactions in the two layers.

In transatmospheric flight, the outer atmosphere presents diurnal, global, and solar activity variations that are not well understood. It also has surprises. Several STS flights have found "pothole" anomalies in the atmospheric density at about 75 km. Shuttle flights instrumented with a high-resolution accelerometer have shown atmospheric density variations as large as 60%.[8] This large variation appears to be random. It also occurs in the altitude regime where a plane change maneuver would take place.

Future aerospace vehicles will begin to operate at hypersonic speeds between the altitude limits of existing aircraft and spacecraft. The vehicles include aero-assisted orbit transfer vehicles or returning lunar and Mars vehicles, new launch vehicles, an aerospace plane, and a space station crew emergency rescue vehicle. These vehicles variously will need the operational flexibility of long downrange, high crossrange, or synergetic plane change maneuvers. Some of these vehicles must be able to use the "thin air" to maneuver as well as to adapt to its variations.

Future flight vehicles must be able to accommodate the uncertainties and variabilities of the outer atmosphere in their designs and performance margins. For engineering design and development of these vehicles, significant advances are required in our understanding of both the static and dynamic properties of the outer atmosphere.

## Tethered Outer Atmospheric Research Capability

The use of tethered research spacecraft to conduct outer atmospheric research (OAR) has been discussed recently.[3,9-17]

### System Description

The purpose of the tether, of course, is to allow a research spacecraft to be deployed some distance away from an orbiting "mother" craft down to lower altitudes. From the Shuttle Orbiter at about 200 km, a deployed subsatellite would be able to traverse the outer atmosphere for extended periods to acquire global coverage. Figure 3 is an artist's rendering of a tethered research craft that is shaped to permit greater atmospheric penetration and is showing aerodynamic heating as a result. Alternatively, it has been proposed that an expendable tethered research craft, "piggy-backed" into unused payload capacity, might be deployed from the second stage of a Delta launch vehicle. Such a capability could provide frequent opportunities to acquire limited data at many different combinations of inclination, altitude, and geographic location.

A joint U.S.-Italian flight system called the Tethered Satellite System (TSS) will provide a reusable capability.[18] The scheduled first experiment (TSS-1) will conduct electrodynamics experiments with a 20 km tether deployed from the Shuttle Orbiter outward from the Earth. The proposed TSS-2 would be an outer atmospheric experiment that would deploy a 1.5 m spherical body at the end of a 100 km tether down into the at-

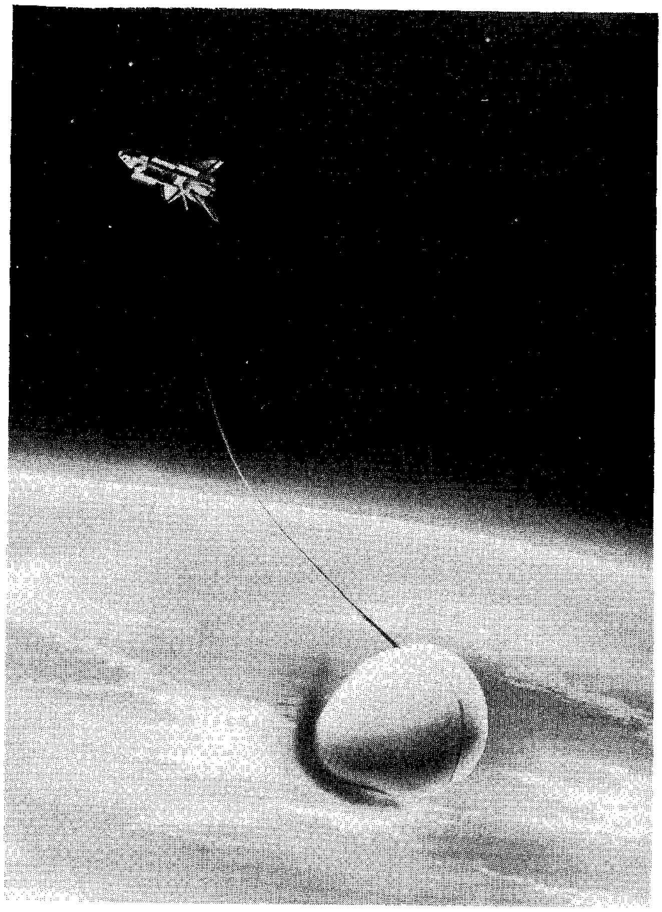

Fig. 3 Tethered outer atmospheric research craft.

mosphere to about 130 km. TSS-1 is scheduled to fly in early 1991; TSS-2 is manifested for late 1994.

A graphic depiction of the tether configuration[12] as it penetrates to about 100 km is shown in Fig. 4. As the depth increases, the drag from even the very sparse atmosphere causes the tether and the tethered body to lag behind. Studies[13] have examined the dynamics of the system as well as tethered body aerodynamic shapes that would permit even deeper penetration into the atmosphere.

#### Technology Requirements

The depth to which a downward-extending tether can penetrate the atmosphere will depend on the technology of the tether itself, controls for the tethered system, research instrumentation, and research craft design. High temperatures and dynamic behavior appear to offer the greatest technology and systems challenges.[10] As the research questions require and the capability can be made available, tethered research will penetrate deeper and deeper into the atmosphere.

The progression of technology advances that will be required to "push" the tethered research capability deeper into the atmosphere is shown graphically in Fig. 5.[11] The unfamiliar operational characteristics of a tethered system and uncertainties over its control will require flight experiment validation precursory to any extensive OAR experimentation. The TSS-1 experiment is probably not analogous enough to provide sufficient validation. The proposed TSS-2 experiment could serve that purpose.

Studies[15] indicate that the TSS-2 probably cannot extend below about 130 km because of the temperature buildup in the tether materials and spherical research craft. Further studies based on current models of the outer atmosphere and tether system dynamics indicate that improved tether materials and control system technologies will be required to permit a tethered craft to extend down to as low as 100 km.[12-13]

Existing measurement methods and instrumentation techniques for atmospheric experiments appear adequate to conduct the desired research down to about 120 km for atmospheric science and to about 100 km for aerothermodynamics. However, specific sensor and instrument technologies must be developed to meet requirements of sensitivity, resolution, response, and range for this research. If research is to be conducted below these altitudes, then the definition and development of entirely new measurement methods and advanced instrumentation techniques will be required.[3]

For the tethered craft to go below 100 km, technologies for advanced tether materials (high temperature, high strength, lightweight), tether control systems (operational, aerodynamic, and thermal), and "penetrating" aerodynamic design will be required. Dynamic simulations of tethered systems performance below 100 km have been conducted.[13]

#### Research Requirements

This section is composed of referenced descriptions of outer atmospheric research interests, issues, and requirements. It is presented in this fashion so as to retain several perspectives at this early stage of identifying possible research agenda.

Fewer missions will be needed for the aerothermodynamic research because global and temporal factors should not be as important as for atmospheric science research. A "tethered research vehicle" is mentioned by Hurlbut[19] as a possibly significant tool for conducting outer atmospheric research directed toward future hypervelocity flight requirements. Hurlbut states:

> I recognize its (the tethered research vehicle) regimes are substantially different from those of the free-flight entry research vehicle but initially it has significant advantages; it provides steady level flight at altitudes from Shuttle down to perhaps 110 km, it is reusable, and it is far less costly. Possibly it can overlap the upper altitude limit of continuum computational fluid dynamics. The vehicle can accommodate most of the experiments we have heard about here. It will permit a flexible strategy for ordering experimental programs.[19]

For aerothermodynamics, tethered satellites will make available both "real" flow conditions associated with the high-velocity, low-density flight regime and a scope of measurement capability that cannot be realized in Earth laboratories. One of the principal research interests deals with gas/surface interactions, both on- and off-surface. A second research interest is the phenomenon of thermomolecular flow affected by cavities and orifices. A third research interest relates to flowfield characterization both at the surface and at standoff locations, focused on higher density conditions at the lower altitudes. A fourth research interest concerns the catalytic-wall phenomenon, which results in increased surface heating from catalytically enhanced recombination of dissociated air.[3]

As the proposed tethered system for atmospheric research becomes better defined and more credible, the early, important research applications can be more specifically defined. Examples of such definition are found in Refs. 16-17, which address research parameters, instrumentation needs, and experiment classes.

> It is clear that, while a single atmospheric science mission could provide data of enormous value, a number of missions will be required to provide the necessary global coverage and to fully delineate both the longer-term and the transitory effects. In this connection, some of the atmospheric science issues will require polar or near-polar orbits for their resolution, while lower-inclination orbits will be important to the resolution of others. A low-inclination orbit for the first mission(s) would be quite acceptable, with higher-inclination missions to follow. Note too that resolution of some of the issues will either require (as in the case of flux determinations) or will be

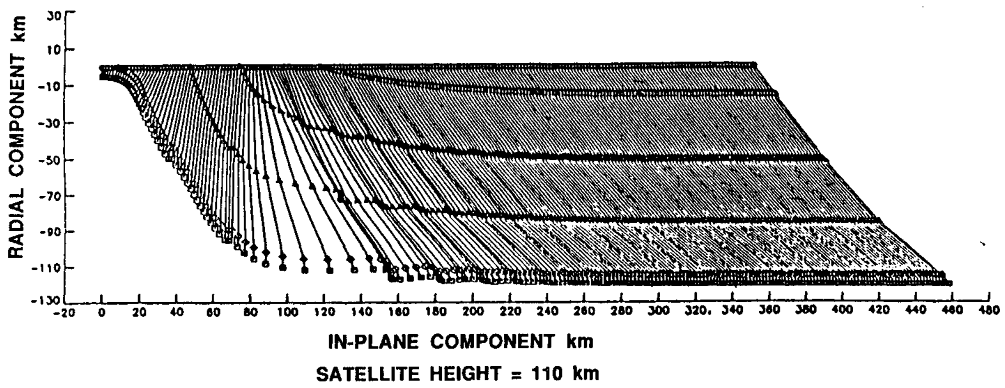


Fig. 4 Configuration of downward deployed tether (from Ref. 13).

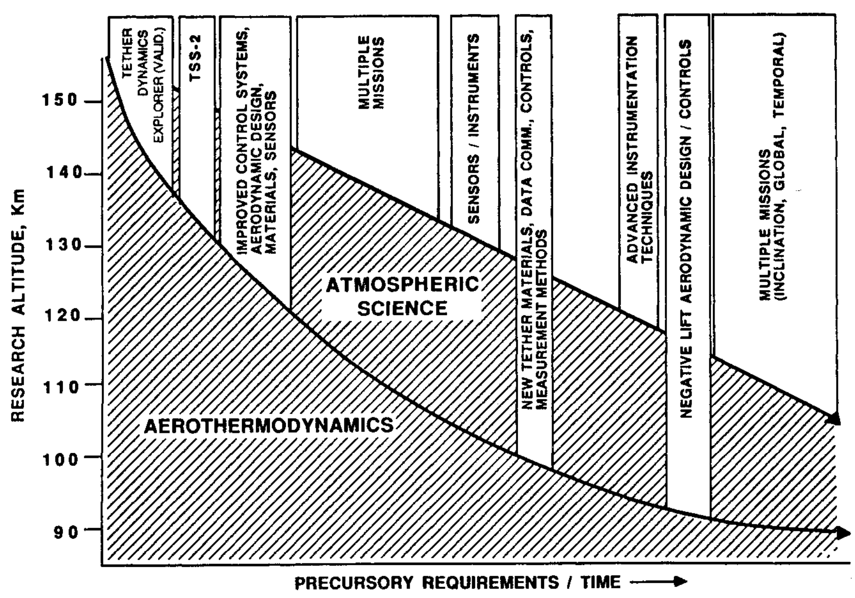


Fig. 5 Evolutionary technology requirements (from Ref. 11).

very significantly enhanced by simultaneous data obtained at different heights.[3]

Simultaneous observation of a number of parameters is required on as close to a global basis as possible and for various levels of solar and geomagnetic activity. These data must be obtained mainly for the height range 100–130 km and will require the use of in situ methods of observation. It is clear that the only way they can be obtained is through an observational program utilizing the TSS or a similar tethered probe and the importance of such a program to atmospheric science cannot be overemphasized.

Improved knowledge of minor constituent chemistry and transport processes in the lower thermosphere might also prove to be of considerable practical importance. It is entirely possible, for example, that the downflow of (NO) created in the lower thermosphere during geomagnetic storms may have a very significant effect on the chemistry of mesospheric ozone and on the ozone balance at lower heights.[3]

For the purpose of exploring

the lower thermosphere from 100 to 130 km... a neutral mass spectrometer having the capability of distinguishing between ambient gases and contaminant species (from the instrument or the vehicle) is necessary to determine ambient species identities and abundances... One goal of such an experiment is to measure total hydrogen content (H, $H_2$, $H_2O$, or $CH_4$) and use these data to improve the estimate of the global escape flux of hydrogen. Photochemical processes thought to be important in controlling the abundances of these species can be verified by such measurements. The ability of the instrument to make near simultaneous measurements of the vector velocities of various constituents will be useful in understanding the dynamics of the lower thermosphere. A well-documented feature of the region between 110 and 120 km is the level known as the turbopause, which is the transition level between the homogeneous mixing of the lower atmosphere and the diffusive separation of the upper thermosphere. Below the turbopause, nonlinear "breaking" of large amplitude, upward-propagating gravity waves produce turbulent eddies. Thus turbulence provides the mechanism for the downward transport of insolation. Meteoric ablation is a major source of metallic atoms. Variations in their concentrations may be controlled by gravity waves and the mapping of such variations is an effective way of determining the amplitudes, wavelengths and the extent of gravity wave activity at these altitudes.[14]

Further progress in our understanding of both the neutral and charged-particle components of the Earth's upper atmosphere is critically dependent on data from the height range between 90 and 130 km. Most of the energy deposition and the other important processes that control the atmosphere at greater heights occur in this region.... Fortunately, few problems are likely to arise in utilizing existing instruments and techniques (in a tethered probe) at heights as low as 125 km. Ultimately, however, it would be advantageous to go to lower heights. Here significant problems can be expected in both the functionality of the instrumentation and the interpretation of results as a result of environmental factors resulting from the velocity of the probe and the greater density of the atmosphere.[15]

**Research Program**

As is evident from the complexity depicted in Fig. 1 and temporal variability indicated in the text, any comprehensive mapping of the characteristics of the outer atmosphere will require a long-term research program. Such a program will require many flight missions covering altitude, latitude, temporal, and global variations.

The use of expendable multistage launch vehicles may offer the earliest opportunity to conduct such research. Use of the second stage of a Delta vehicle as a "mother" craft would offer the opportunity to conduct both early tether validation and later tethered research experiments. Perfection of this type of flight experiment could offer a less costly, more frequent means of gathering tethered outer atmospheric data, although for shorter experiment times.

The TSS is proposed to provide a reusable deployment/retrieval system. After the proposed TSS-2 experiment, two types of tethered flight experiments may then evolve. To conduct aerothermodynamic studies to guide engineering design, tether-deployed research craft that model future aerospace vehicles will be used. This is the earlier STARFAC concept of a "flying" wind tunnel.[12-13] To conduct scientific studies, the research craft should perform as instrumentation carriers that are minimally intrusive in perturbing the measured environment. Both types of experiment later will require aerodynamic configurations that cause penetration deeper into the atmosphere to about 90 km. Depending on the research required, candidate configurations include lower drag profiles, an asymmetric blunt body, or negative-lift airfoil shapes.

## Conclusions

The outer atmosphere of the Earth from about 90 to 150 km is a relatively unexplored region of growing interest for scientific investigation and aerospace operations. The region has diverse and significant roles in the functioning of Earth systems and human endeavors. The emergence of the concept of using a tethered research satellite to map the outer atmosphere on a global basis offers a potential capability where none existed before. A collaborative effort between the research users and the capability developers will be required to justify, develop, and validate the capability, and to carry out a research program.

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