Downward-Deployed Tethered Platforms for High-Enthalpy Aerothermodynamic Research

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The data describing aerothermodynamic and aerodynamic interactions at altitudes above 50 km are extremely limited because of the relative inaccessibility of the region to research vehicles of any sort. This paper addresses the practicality of using downward-deployed satellites tethered to an orbiting host vehicle to obtain steady-state data in the upper continuum as well as the transition and molecular flow regimes. Recent studies predict that altitudes as low as 90 km can be achieved with aerodynamically shaped satellites, and that tether temperature will be the altitude-limiting parameter.

Introduction

THE flight systems that operate in the continuum and noncontinuum flow regimes have traditionally been developed from data bases generated in wind tunnels. These data bases are supplemented by flight-test data, and by analytical computer models, the accuracy of which is validated by such data. Hypersonic vehicles will of necessity be designed to operate in the flight regime where transition, slip, and free molecular flow conditions exist. Ground-based test facilities are not and will not be capable of providing adequate data for verification of the computer models because of a number of practical limitations. These include wall effects, the inability to simultaneously simulate the Mach, Reynolds, and Knudsen numbers expected in flight, the differences in tunnel and real-gas atmospheric composition (which prevents the duplication of nonequilibrium real-gas processes), and low measurement resolution due to the size of the test model.[1]

At altitudes between 50 and 150 km, the acquisition of steady-state aerodynamic, aerothermodynamic, and atmospheric science data has been severely constrained by the relative inaccessibility of the region. Too high for balloons or research aircraft and too low for satellites in circular orbits, data in this region have been obtained under transientory conditions with sounding rockets, satellites in highly elliptic orbits, or, to a lesser extent, the re-entering Space Shuttle. The relatively short duration of such flights and the inability to maintain a constant altitude has in turn limited both the amount and quality of the data. However, an accurate determination of the aerothermodynamic forces and gas-surface interactions are necessary to verify and improve the accuracy of the computer models. This was clearly demonstrated on one of the early Space Transportation System (STS) missions, where approximately 10 deg additional body-flap extension was required than was predicted by the then best available model.[2]

Siemers et al.[3] and Freeman[4] have discussed several advanced hypersonic vehicles that will routinely operate in noncontinuum flow, including orbital transfer vehicles (OTV), which will use aeroassisted braking during return from geosynchronous to low-Earth orbits (LEO); and entry research vehicles (ERV), which will obtain data in LEO and below. The OTV will require a significant reduction in velocity while aerobraking at 80–90 km, and will most likely have a low lift-to-drag ratio (L/D). Since a LEO rendezvous capability is also required, a low-to-medium cross-range capability will be necessary. The ERV, on the other hand, will require a high cross-range capability, and will be configured with a correspondingly high L/D. The prototypes of these vehicles, as well as several currently manifested experiments measuring pressure, acceleration, and gas composition during STS reentry, will provide valuable aerothermodynamic data and some validation of the computational codes required for advanced vehicle design. Flight profiles, however, will still cause the data to be obtained under rapidly changing, or, at best, limited steady-state conditions.

Because of its cross-range maneuvering capability, the ERV is perhaps the most promising approach for obtaining quasisteady data. Sustained steady-state data, including the effects of diurnal variations in ambient temperature, density, and atmospheric composition, can best be obtained with a downward-deployed instrumented platform tethered to an orbiting host vehicle. Several such platforms are currently under study and are conceptually mature. Several examples are 1) the second Tethered Satellite System (TSS-2), a cooperative program of NASA and the Agencia Spaziale Italiana (ASI) for the downward deployment and retrieval of a 1.6-m-diam spherical satellite on a 100-km-long tether; 2) the Shuttle Tethered Aerothermodynamic Research Facility (STARFAC), which is aerodynamically shaped to achieve lower altitudes; and 3) the Tethered Dynamics Explorer/Tethered Atmospheric Probe (TDE/TAP), a nonrecoverable smaller satellite for obtaining deployment dynamics and other data. Although the host vehicle is most often considered to be the STS, the deployment of a satellite from a free-flying expendable launch vehicle, such as

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the second stage of a Delta-II[5] or from another satellite,[6] has recently been proposed. In either case, the host vehicle is required to provide the deployment mechanism, to expend sufficient energy to maintain orbital altitude during the mission, and, in the case of the STS, to retrieve the satellite at the conclusion of the mission.

Tethered Satellite System

In a brief review of the evolution of the applications of tethers in space, Bekey[7] attributes one of the first practical studies of the TSS to Professor Colombo and his co-workers at the Smithsonian Astronomical Observatory. Subsequently, Karr[8] proposed the use of the TSS to obtain data in the atmosphere, and Webster[9] has reviewed geophysical and atmospheric science research with tethered systems over the altitude range of 90–400 km. Carlomagno et al.[1,10,11] also discussed accessing the atmosphere to altitudes between 100 and 150 km by towing an aerodynamically shaped model tethered to the STS to represent a space-based wind tunnel for measuring interactions under real-gas conditions. They have proposed the Shuttle Continuous Open Wind Tunnel (SCOWT), which is a measurement system incorporated into the TSS and other satellites that are to be deployed downward from the STS on a tether of sufficient length to reach an altitude at which the gas-surface interactions become significant. The primary objectives of the SCOWT are to investigate the energy and momentum transfer between the satellite and the ambient atmosphere; investigate the gasdynamic processes in the frontal shock layer and the associated boundary layer; characterize the ambient atmosphere; study the physics and chemistry of high-altitude aerothermodynamics; and support the development and validation of the theoretical models and computational codes of free-molecule/transition flowfields.

The TSS (Fig. 1) consists of two major elements: the deployer, which is mounted on an enhanced Spacelab pallet in the Shuttle bay; and a 1.6-m-diam spherical satellite having an allowable payload of about 50 kg. The deployer consists of an electrically driven reel mechanism that can control the stability of the satellite during the deployment by adding or decreasing tension on the tether as required. The first mission (TSS-1), which is currently manifested for early 1991, will be an upward deployment of a 20-km-long conducting tether to study electrodynamic, magnetic, and plasma properties in the ionosphere. For this mission, the STS will be in a circular orbit at approximately 300 km. The second mission (TSS-2), which is currently proposed for a 1994 or 1995 launch, will be a 100-km downward deployment with a nonconducting tether from approximately 200 km. The actual lower altitude reached will lie between 120 and 130 km depending on atmospheric density at the time of deployment. The TSS-2 will therefore provide an opportunity to obtain data concerning the rarefied gas dynamics as well as verifying the deployment dynamics and control law models. ASI and its prime contractor, Aeritalia, have responsibility for the satellite; NASA and its prime contractor Martin-Marietta are responsible for the deployer and the tether. Both NASA and ASI will furnish the selected engineering and science experiments.

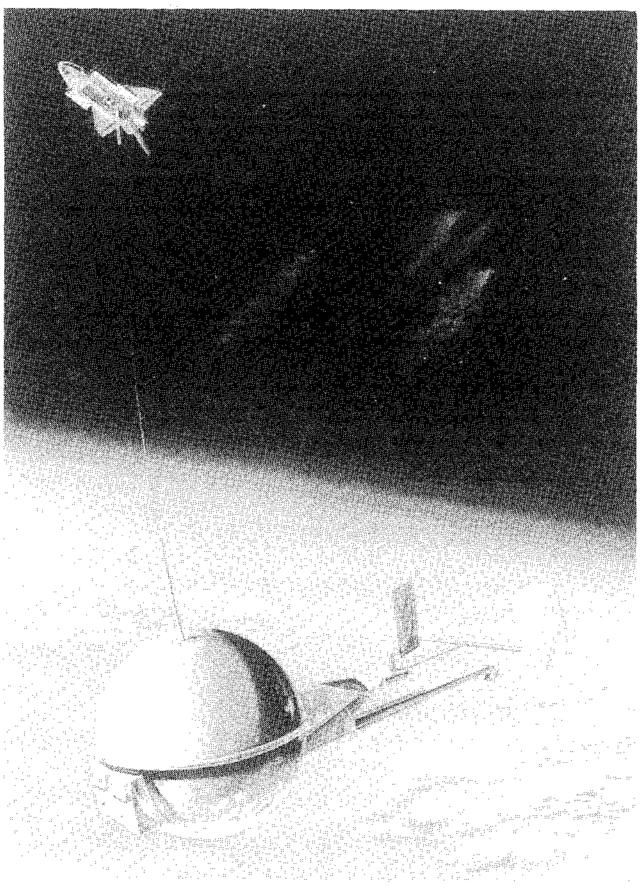

Fig. 1 Tethered Satellite System-2 (TSS-2).

Shuttle Tethered Aerothermodynamic Research Facility

Because of the spherical configuration of the TSS, it is predicted that reaching an altitude of approximately 110 km would require a tether 150 km long. The objective of the Shuttle Tethered Aerothermodynamic Research Facility (STARFAC)[3] (Fig. 2) is to extend the operational capability to the lower altitudes with the shortest possible tether in order to increase the aerothermodynamic interactions measured. It must be emphasized that the concept of STARFAC is a recoverable vehicle for repeated aerothermodynamic research under varying conditions, and will not necessarily consist of a single vehicle of a specific shape. It is, rather, more likely that the vehicle will evolve along with the data it obtains. The first precursor of the STARFAC will be the spherical TSS-2. Various configurations having a range of L/D are being examined for advanced missions. As a first consideration, a vehicle with negative lift would appear to be desirable; however, our model predicts that the accompanying increase in drag and control requirements quickly overcome any advantage that might be realized. Studies of a vehicle having reduced drag that have recently been initiated suggest that a more stable deployment to lower altitudes is achieved. It is further predicted by our model that the temperature of the tether would approach 950 K at 90 km, so that practical materials considerations would impose a limiting altitude for the STARFAC.

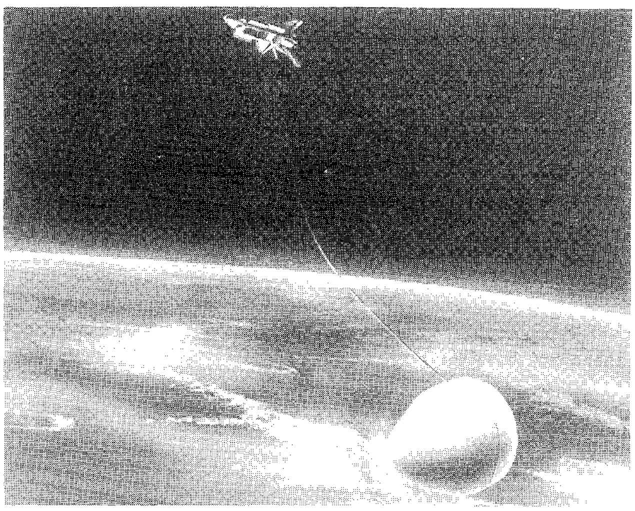

Fig. 2 Shuttle Tethered Aerothermodynamic Research Facility (STARFAC).

It has also been suggested that lower altitudes could be reached by using thrusting to overcome the effects of drag. However, our calculations have shown that this is likely not a practical solution. Typical data obtained from our model show that an altitude of 69 km could theoretically be reached, but with a tether temperature of 2200 K, a tension of 685 N, and a significantly increased requirement for real-time attitude control.

Tethered Dynamics Explorer/Tethered Atmospheric Probe

It is apparent that both the TSS/SCOWT and the STARFAC are relatively large, sophisticated systems. In addition, design of the satellite and deployer systems and the mission profiles are dictated by safety and operational constraints of the STS. Flight scheduling must compete with manifesting of other experiments, so that flight opportunities will necessarily be limited.

The concept of a simplified system consisting of a small satellite to be deployed as a secondary payload from an expendable launch vehicle (ELV) such as a Delta-II, or as a primary payload on a smaller ELV, is currently being defined by NASA (Fig. 3). Depending on the data to be obtained, these are designated Tethered Dynamics Explorer (TDE) or Tethered Atmospheric Probe (TAP). The first objectives of the TDE are to obtain data on tether deployment rate and shape, tether tension, and acceleration and attitude of the satellite in order to validate computer models of the deployment. Other engineering and scientific data may also be obtained on a more limited but more frequent basis that can be accomplished with the TSS or STARFAC. These data might also be useful in defining the TSS-2 mission; however, the deployment and mission profiles will have little similarity to that of the TSS, and hence, they will be applicable only in the generic sense. The TDE deployment is not, therefore, a percursor experiment for the TSS, nor will the TDE missions provide the type and quantity of data that will be obtained with the TSS and STARFAC. The TDE will, however, be a precursor system leading to the deployment of instrumented subsatellites from ELV or from larger host satellites, which may be placed in polar as well as inclined or equatorial orbits. The host may in this case have some capability of subsatellite retrieval and redeployment, so that seasonally dependent data may also be obtained. These satellites will have the primary objective of obtaining geophysical and aerothermodynamic data, and will in fact be a Tethered Atmospheric Probe (TAP). The TAP satellite will include communications as well as instrumentation, so that data will be obtained independent of the ELV during the re-entry as well as the on-orbit phase.

The TDE/TAP deployer is that which is being developed for the NASA Marshall Space Flight Center Small Expendable Deployer System (SEDS).[12] It consists of a canister containing the tether and the associated deployment control and turns counting circuitry. Deployment and control of the experiment may be initiated by ground command or by the ELV, and would typically consist of the following sequence: power-on; jettison satellite and initiate experiment; initiate data transmission; activate tether cutter; and terminate the experiment.

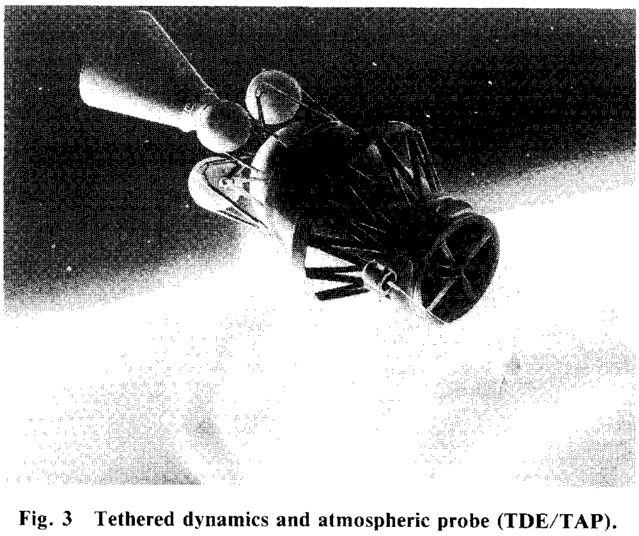

Fig. 3 Tethered dynamics and atmospheric probe (TDE/TAP).

Unlike the TSS deployer, which provides tension and therefore positive control of the deployment trajectory at all times during the mission, the SEDS is a low-tension deployment device that provides significant tension only when the tether is fully deployed. Therefore, the satellite will initially lead the ELV with the tether making an angle of approximately 60 deg above local vertical. When the tether is deployed and tension is applied, the satellite will swing downward. Depending on the data to be obtained, the satellite will either be released when local vertical is reached, will be allowed to swing through local vertical, or will be stabilized about local vertical for the remainder of the on-orbit portion of the experiment.

Deployment Dynamics

Two questions concerning the tethered platforms are the deployment dynamics (i.e., the behavior of the satellite and tether during deployment), and the limiting altitude that can be reached. Although useful atmospheric science data can be obtained from the altitude of deployment to whatever lower altitude can be reached, altitudes below $\approx$ 130 km are required if meaningful aerothermodynamic interactions are to occur. Although temperature and drag restraints may result in a lower altitude limit of $\approx$ 90 km, it may be possible that additional deployment can be obtained through the use of high-temperature materials and suitably shaped vehicles having reduced drag. Consequently, computer-based studies to determine the most effective type of platform that can realistically be deployed to the lower altitudes and to better predict the lower altitude limits are being carried out by NASA, the University of Naples, the Smithsonian Astrophysical Observatory, and others.

Since the STARFAC is considered to be an extension of the "baseline" TSS-2, a considerable effort is underway at the NASA Langley Research Center to study the deployment dynamics and control laws for both spherical and aerodynamically shaped vehicles. These studies are generally based on the pioneering work of Rupp[13] and on the SKYHOOK computer model[14] developed at the Smithsonian Astronomical Observatory. Both Rupp's work and the SKYHOOK have been substantially modified for the NASA Langley deployment model.

SKYHOOK is a program of great generality and analytical sophistication with the capability of analyzing a broad range of tether-related scenarios. The STS and the satellite are represented by mass points, while the tether may be included in either or may be represented separately as a series of independently spaced mass points. Both thermal and elastic expansion of the tether, as well as solar and lunar perturbations, electrodynamic forces acting on the tether, and the effects of gravitational fields may be induced. Most importantly for the STARFAC simulations, atmospheric drag on the tether and the oblateness of the Earth may also be incorporated into the calculation.

With all of its many attributes, SKYHOOK was not designed for simulating deployments at the altitudes addressed by STARFAC. Accordingly, SKYHOOK has been modified to include lower altitude calculations, and a deployment routine specific to the STARFAC has been substituted, which more accurately models the deployment and retention of the satellite at a target altitude for the required number of orbits. To meet STARFAC objectives, the altitude of the satellite during the measurement process must be stable. After considering both periodic orbital maneuvers and sustained thrusting by the STS, the modified SKYHOOK program clearly demon-

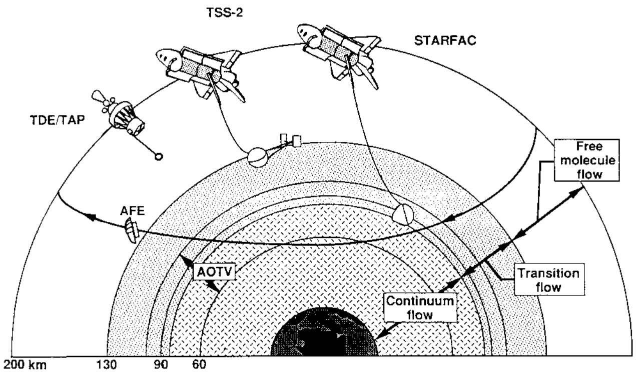

Fig. 4 Regions accessible by tethered research satellites.

strated that sustained thrusting to produce an increased velocity of 82 m/s is sufficient to maintain the required altitude when the tether is fully deployed. Elliptical and equatorial and inclined circular orbits have been examined. The equatorial calculations showed 1) that deploying the "baseline" spherical TSS configuration to altitudes between 100 and 200 km is practical; 2) that deploying the TSS below 100 km is impractical due to drag and excessive tether length; and 3) that below about 120 km the tether temperature may become excessive, thus requiring the use of materials with high melting points.

Since the purpose is to obtain steady-state data at a nearly constant altitude, highly elliptical orbits have been eliminated from consideration because of the rapidly changing conditions and because these orbits introduce very large oscillations into the system without substantially lowering the temperature of the tether and satellite. Although equatorial circular orbits produce the most unperturbed data, the inclined circular orbit that most nearly represents the real-life conditions also shows acceptable levels of out-of-plane oscillations resulting from side forces induced by the rotating atmosphere and density variations with latitude.

Measurements and Instrumentation

The regions accessible by the TDE, TSS, and STARFAC are shown in Fig. 4, and typical atmospheric properties at these altitudes are listed in Table 1.[5] For comparison, the altitudes at which the Aeroassit Flight Experiment (AFE) and the Aerobraking Orbital Transfer Vehicles (AOTV) will operate is given. The success of any research program is of course dependent upon the ability to obtain data of sufficient quality and accuracy. The outer-atmosphere research described here introduces instrumentation requirements that have not been fully defined in either ground-based or flight systems. These measurement requirements have been qualitatively addressed and candidate measurement methods have been identified (Table 2); however, quantitative definition and the development of the appropriate measurement systems remains to be done.

These measurements fall into several categories[1]: determination of the state vector (position, velocity, attitude, acceleration, and tether tension); freestream characteristics (composition, density, and charge state); gas composition of the shock or boundary layer (both immediately adjacent to the surface and in profiles across the layer); and satellite/flowfield interactions (drag, acceleration, heat flux, and skin temperature). Although many of these measurements can be made using instrumentation based on existing technology, at least moderate engineering development and some integration is required for each. In particular, aerothermodynamic and gasdynamic data concerning the interaction of the vehicle with the rarefied atmosphere requires highly quantitative measurements of the gas composition and of the charge state and energy of ionized species in both the freestream and boundary layer.

Analysis of the gas composition in the freestream and near the vehicle surface can most readily be accomplished with mass spectrometry. The freestream mass spectrometer will use advanced but existing engineering concepts based on previous instrumentation flown in space. Most satellite mass spectrometers have been designed to measure freestream properties of the atmosphere, including the energy distributions of charged ions, and are well-documented in the literature.[15,16] Measurement of the gas composition in the boundary layer at the vehicle surface is more difficult, and the concept of a nonpumping effusive inlet coupled with a double-focusing mass spectrometer is currently being studied at NASA Langley.[17] A number of measurement techniques have been considered to measure the gas composition across the shock-layer profile.[18,19] The candidate methods are mostly based on optical spectroscopy or electron beam techniques; however, this is an exceedingly difficult measurement to make and to date none of the methods have been proven in practice.

Instrumentation technology for the measurement of temperature and low-level heat flux exists, but the degree to which

Table 1 Typical physical properties

Regions			Altitude, km	Temperature, K	Pressure, Torr	Number density, N/cm^3	Mean molecular weight	Research vehicles
Heterosphere		Exosphere						Satellites
(diffusive	Ionosphere	↓	600	1000	2.1×10^{-10}		11.51	↓
mixing)	↓	Thermosphere	400	990	2.6×10^{-9}		15.98	↓
↓	↓	↓	300	976	1.4×10^{-8}	6.5×10^{8}	17.73	↓
↓	↓	↓	200	854	8.4×10^{-7}	7.2×10^{9}	21.30	↓
Homosphere	↓	Mesosphere	100	210	2.4×10^{-4}	1.1×10^{13}	28.40	Sounding
(turbulent	↓	↓	90	176	1.4×10^{-3}	7.6×10^{13}	28.77	rocket
mixing)	↓	↓	80	177	7.9×10^{-3}	4.2×10^{14}	28.96	↓
	↓	↓	70	211	4.4×10^{-2}	2.0×10^{15}	28.96	↓
↓	Ozonosphere	↓	60	253	1.9×10^{-1}	7.2×10^{15}	28.96	↓
↓	↓	Stratosphere	50	274	6.6×10^{-1}	2.3×10^{16}	28.96	Balloons,
↓	↓	↓	40	268	2.2×10^{0}	8.1×10^{16}	28.96	sounding
↓	↓	↓	30	235	8.6×10^{0}	3.6×10^{17}	28.96	rockets
↓	↓	↓	20	219	3.9×10^{1}	1.7×10^{18}	28.96	
↓		Troposphere	15	211	8.5×10^{1}	3.9×10^{18}	28.96	↓
↓			10	231	1.8×10^{2}	7.7×10^{18}	28.96	↓
↓			5	266	3.7×10^{2}	1.3×10^{19}	28.96	↓
			0	291	7.6×10^{2}	2.5×10^{19}	28.96	↓

Table 2 Aerothermodynamic measurements and instrumentation with tethered satellites

Measurements	Candidate methods
Surface temperature; temperature distribution	Thermocouples
Heat flux rate	Thermocouples, calorimeters
Internal temperature	Thermocouples, radiometers
Internal pressure	Thermopile, capacitance gauges
Dynamic surface pressure; pressure distribution	Capacitance, variable reluctance pressure gauges
Acceleration	Accelerometers, gyroscopes
Attitude	Magnetometer, gyro, sun sensors
Location	Laser radar, GPS
Freestream gas analysis	Freestream mass spectrometer
Near-surface boundary layer analysis	Boundary layer mass spectrometer, specific chemical sensors
Flow field profiling	Rayleigh scattering, e-beam, IR, laser fluorescence
Gas density	Pressure, temperature, mass spectrometer, derivable from other measurements
Surface catalysis	Heat transfer, mass spectrometer
Gas/surface interactions	Thermocouple, heat transfer, mass spectrometer
Glow phenomenon	Photo-optical spectral analysis
Tether tension; strain	Tensiometers, accelerometers, fiber optics
Tether temperature	Fiber optics, reflected acoustic or electrical wave propagation, resistance

currently available sensors will be applicable has not been established. In particular, gas-accommodation coefficients, and the effects of catalysis, emittance, oxidation, contamination, and free electron concentrations on measurement accuracy are of concern. The magnitude of these effects and the minimization of errors through calibration and correction procedures are currently being examined at NASA Langley.

Summary

In conclusion, the "tethered wind tunnel" concept has been discussed and considered to be a valuable adjunct to other flight programs proposed to obtain aerothermodynamic and atmospheric data. The TDE, TAP, TSS-2, SCOWT, and STARFAC have the additional capability of obtaining steady-state data over the period of one or more orbits at a sustained altitude. Modifications of existing models to address the operational parameters of the extended downward deployments have been accomplished. It has been determined that the initial deployment of the spherical TSS-2 to altitudes near 130 km is feasible, and that deployments to about 90 km should be possible using aerodynamically shaped vehicles and high-temperature tether materials.

It has also been determined that the practical implementation of the SCOWT/STARFAC missions is dependent upon the development of appropriate scientific and engineering instrumentation. The measurement requirements defined for the preliminary missions indicate that engineering development and integration are in all cases required, although most of the basic measurement technology is in place. The measurements to be performed have been qualitatively defined, and candidate instrumentation identified.

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