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Downward-Deployed Tethered Satellite Systems, Measurement Techniques, and Instrumentation: A Review

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Data describing spacecraft atmospheric interactions in the lower terrestrial thermosphere (altitude range between 90 and 200 km) are extremely limited due to the relative inaccessibility of this region to research vehicles. Atmospheric measurements in the lower thermosphere are sparse when compared with measurements on satellites at higher altitudes. Downward-deployed tethered satellites are being developed to allow access in a global sense to this important region of the atmosphere. This paper reviews a number of tethered satellite systems, emphasizing downward-deployed systems to measure properties in the lower thermosphere; the physics and chemistry of the lower thermosphere; the interactions of the lower thermosphere with high-velocity tethered satellites; and the performance capabilities of existing and new instrumentation to measure atmospheric, aerodynamic, and aerothermodynamic properties that include radiative emission (glow), magnetism, and the distribution of the neutral gas, excited species, ions, and electrons. It is concluded that these tethered satellite systems, when implemented, offer a unique opportunity to investigate regions of the atmosphere previously inaccessible to conventional satellites.

Introduction

NASA and Agenzia Spaziale Italiana (ASI), the Italian Space Agency, have developed and plan to fly a tethered satellite system, TSS-1, in the second half of 1992. TSS-1 will be upward deployed and is designed to demonstrate tether dynamics and perform scientific studies on the electrodynamics of conducting tethers. The satellite and the Space Shuttle contain a large number of scientific instruments to perform these studies.[1] NASA and others are determining the feasibility of a number of follow-on downward-deployed tethered satellite missions (see Fig. 1) to study the aerodynamics and aerothermodynamics of hypersonic vehicles that traverse the lower thermosphere: 1) The Tethered Satellite System Atmospheric Verification Mission (TSS-AVM)[2] is proposed as the second deployment and would be used to study aerodynamic forces, heating, and tether control at altitudes as low as 110 km. The satellite will be simple in design, will not be recoverable, and will contain minimum instrumentation; 2) TSS-2[3] would be fully instrumented to characterize both vehicular aerodynamics and aerothermodynamics and atmospheric structure. This satellite mission is currently being studied by both NASA and ASI; 3) The Shuttle Tethered Aerothermodynamic Research Facility (STARFAC),[4] proposed for flight late in this decade, would be fully instrumented and retrievable. This facility, which would fly at altitudes as low as 90 km, would be the first of a series of satellites whose shape and purpose will evolve to solve specific practical aerothermodynamic problems of the 21st century.

In addition to these Shuttle-based missions, NASA has scheduled in the first half of 1993 a low-cost tether mission[5] as a secondary payload on a Delta II launch vehicle. This mission will test the Small Expendable Deployer System (SEDS), which is being designed at NASA Marshall Space Flight Center. The Tether Dynamics Explorer (TDE) payload for this mission consists of instrumentation to study tether dynamics. NASA plans to develop and fly during the 1990s a series of these low-cost flights to characterize tether dynamics, measure the environment around tethered satellites, and test instrumentation for future Shuttle-based missions.

The Shuttle-based downward-deployed missions will be designed to obtain atmospheric data in the lower thermosphere, aerodynamic data on the gas affected by spacecraft flying in this region, and aerothermodynamic data at the gas-spacecraft surface interface. This region of the atmosphere has not been studied in any detail since it is too high for balloons and research aircraft and too low for orbiting satellites. Sounding rockets have probed the region at limited locations, and the Atmospheric Explorer (AE) satellite accessed this altitude range at perigee in its highly elliptical orbit. The High-Resolution Accelerometer Package (HiRAP),[6] flown onboard the Shuttle, has been used to infer atmospheric density in this region during Shuttle ascent and descent; and the Shuttle Upper Atmosphere Mass Spectrometer (SUMS),[7] another Shuttle-mounted experiment, has been used to measure species composition. The Aeroassist Flight Experiment (AFE)[8,9] was

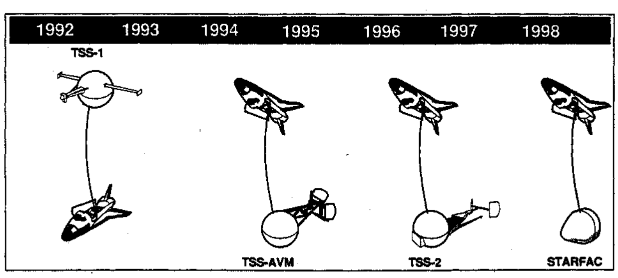

Fig. 1 Scheduled and proposed TSS missions.

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planned to fly in the mid-1990s to probe this region. A summary[10] of the vehicular access to the lower thermosphere can be found in Fig. 2 (this figure is an updated version of the one in Ref. 10). The data gathered on these vehicles are limited in a global sense to isolated points in time and space with the exception of the data gathered around perigee on the AE satellite. To emphasize the advantage of satellite measurement in studying the atmosphere, it is noted that more lower thermospheric data were gathered on the AE satellite missions than on all previous missions. Tethered satellites, which fly in the lower thermosphere, will give access in a global sense to this critical region of our atmosphere.

The purpose of this paper is to describe the measurements and instrumentation required to determine the structure of the lower thermosphere and its effects on high-velocity vehicles like the Shuttle and the proposed National Aero-Space Plane (NASP), which traverse this little known region of our atmosphere. The structure of the lower thermosphere, including the distribution of the neutral gas, ions, electrons, excited species and emissions (glow), and magnetism, is discussed. Atmosphere-spacecraft interactions, including the aerodynamics of a vehicle traversing this region of the atmosphere and aerothermodynamics at the spacecraft surface, are also discussed. A review of the performance characteristics of existing flight-qualified instruments is given, and recommendations are made for the flight development of additional measurement techniques that are needed to improve accuracy, minimize weight and power, and simplify tether scientific instrumentation packages. This report concentrates on the definition of measurements and instrumentation for the TSS-AVM and TSS-2 missions.

Atmosphere-Spacecraft Interactions

This section contains a brief review of 1) the atmospheric properties of the lower thermosphere,[11,12] 2) the effects of the vehicle on the gas in its vicinity (gas phase effects—aerodynamics), and 3) vehicular surface effects (surface effects—aerothermodynamics). The atmospheric properties of the lower thermosphere are not well known in a global sense. Spacecraft are overdesigned due to the lack of information, and we are constantly being surprised by vehicular interactions with the atmosphere (i.e., O degradation, spacecraft glow, etc.).

Neutral Atmosphere

Below about 100 km the atmospheric gas consists mainly of molecular nitrogen and molecular oxygen, and its composition varies little in time and space. Above approximately 100 km the photodissociation of molecular oxygen and diffusion produce an atmosphere whose composition varies considerably in the vertical. Further, the atmospheric density, temperature, and composition vary with the solar cycle, solar activity, time of day, geomagnetism, and seasons. At a given latitude and longitude, the temperature increases with height and approaches a defined exospheric temperature T_e asymptotically. As an example, for medium Sun conditions ($T_e = 1000$ K), the total density, temperature, and composition at 90 km is 7×10^{13} cm^{-3}, 188 K, and 0.78 N_2, 0.20 O_2, respectively, and at 200 km is 7×10^{9} cm^{-3}, 885 K, and 0.40 N_2, 0.56 O, respectively.[13] Atomic oxygen is a highly chemically reactive gas and is difficult to sample properly. N_2 is less reactive, stable, and remains a major constituent in the lower thermosphere. Atomic nitrogen is formed by processes other than photodissociation, has a peak density between 100 and 200 km, and is a minor constituent with composition around 0.05. In addition to these static conditions, the upper atmosphere is dynamic; there are winds, gravity waves, and transport of gas in both the horizontal and vertical.

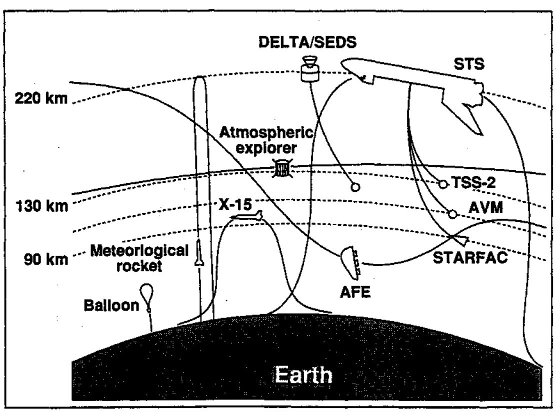

Fig. 2 Vehicular access to lower thermosphere.[10]

Ion Atmosphere

The three predominant positive ions in the lower thermosphere are O^+, NO^+, and O_2^+. O^+ is the predominant ion at altitudes above 200 km and becomes insignificant below 150 km. NO^+ is the largest ion constituent below 200 km. O_2^+ composition reaches its maximum at around 150 km but does not exceed the composition of NO^+. The absence of N_2^+ does not mean that this ion is not formed but that it disappears rapidly by dissociative recombination. Ions exist in the atmosphere in concentrations (10^5 cm^{-3}) much lower than neutral constituents; however, changes with time in charged particle concentrations have been shown to have a major effect on the neutral atmosphere. Ions generally follow magnetic field lines in the upper part of the thermosphere and are swept along with the neutral gas at altitudes less than 130 km.

Atmospheric Electrons

The electron density increases with altitude from a few times 10^4 cm^{-3} at 100 km to approximately 10^6 cm^{-3} at 200 km. The lower thermosphere contains both the E layer (90–160 km) and the F1 layer (above 160 km). The F2 peak is generally above 250 km. The electron density varies considerably throughout this region. This is particularly true in the E layer, where transient abnormal ionization occurs on a more or less regular basis. Motions in the upper atmosphere can give rise to electric fields. Electrons and ions moving in response to these fields and the Earth's magnetic field form an electrical current. Examples of these currents are the large flows around the magnetic pole called the Birkeland current and an east-west current near the magnetic dip equator, at altitudes between 90 and 130 km, known as the electrojet. The charged particle flows can transfer energy to the neutral gas, causing heating and excitation.

Excited Species—Emissions

The presence of excited molecules is demonstrated quite graphically by observed emissions in the ultraviolet, visible, and near-infrared spectrum. These emissions are known as airglow and the aurora. Most of this glow originates in the lower thermosphere from collisional excitation and spontaneous decay of meta-stable states of the atmospheric gas. The gas is excited by photochemical processes that occur in the lower thermosphere. Most of the solar photon absorption occurs in the lower thermosphere, which leads to heating, excitation, dissociation, and ionization of the gas. A complicated combination of current flow, magnetic fields, and neutral winds are thought to contribute to the aurora that occurs at high latitudes and is much brighter than airglow. Interest in emissions has recently increased with the observation of spacecraft glow.

Magnetic Field

The terrestrial magnetic field can be divided into two components: the relatively constant field produced in regions interior to the Earth's surface and the field produced by currents in the upper atmosphere. The interior field has a magnitude of about 30,000 nT; its horizontal component is in the direction of the magnetic North Pole, and its vertical component is zero at the magnetic dip equator and maximum at the magnetic poles. The external component of the magnetic field has small regular variations due to lunar and solar tides (0.01) and larger variations (0.20) during magnetic storms. An electrojet has been used to explain anomalies at the magnetic equator. The interaction between neutrals, ions, and electrons in the presence of the Earth's magnetic field outlines the importance of studying the atmosphere as a whole. In-situ measurements on tethered satellites offer this opportunity.

Gas Phase Effects—Aerodynamics

A high-velocity vehicle traveling through the atmosphere interacts with the gas, producing a gas buildup in front of the vehicle and a reduced gas density behind the vehicle. This effect is demonstrated in Fig. 3, which shows lines of constant number density normalized to freestream density[14] for a sphere traveling at orbital velocity at an altitude of 130 km as calculated with the direct simulation Monte Carlo method.[15] Just in front of the vehicle, the density is a factor of 12 times the freestream (not shown in Fig. 3), decreases with distance from the body, and approaches the freestream density at about a satellite body diameter in the forward direction. The density just behind the vehicle is reduced substantially, reaching a value less than 0.05 times the freestream density.

Below 130 km, the density of the gas near the surface increases to the extent that freestream molecules cannot traverse this gas without having many gas-gas collisions. These collisions heat the gas, and cause excitation and dissociation of molecules. These effects are summarized in Fig. 4, which shows typical flight paths for high- and low-lift vehicles plotted as a function of both altitude (atmospheric density) and spacecraft velocity. The high-lift entry trajectory is typical of the next-generation Shuttle, and the low-lift entry trajectory is typical of NASP. The flight path of the present Shuttle lies between the high- and low-lift curves. Superimposed on this plot are percent dissociation and vibrational excitation for molecular nitrogen and oxygen. All of the effects to the left of the flight-path curve are possible. As an example, at 90 km and orbital velocity (approximately 8 km/s), a large fraction of N_2 is dissociated, all of O_2 is dissociated, and vibrational excitation is possible for most of the molecular atmospheric species.

The high-velocity vehicle also produces a flow of charged particles, ions and electrons, in its vicinity and onto its surfaces. This current, in the presence of the Earth's magnetic field, can substantially change the local electric field, cause spacecraft charging, and further complicate the plasma near the vehicle.[17] The plasma (substantial in the lower thermosphere) can also affect the local magnetic field near the vehicle. At altitudes below 130 km, the plasma caused by the ion sheath around the vehicle is dense enough to cause attenuation of radio waves.

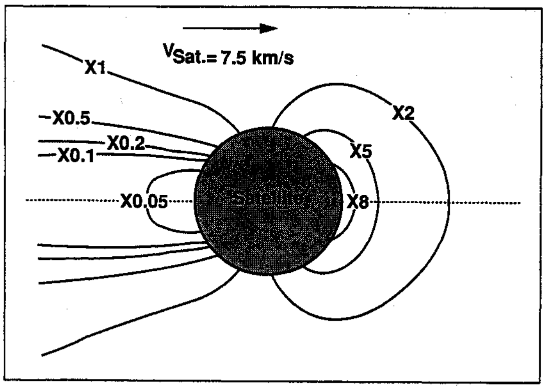

Fig. 3 Number density normalized to 1.89×10^{18} cm^{-3}, T(atmosphere) = 431.5 K for a 1.6-m-diam sphere, surface temperature = 350 K.

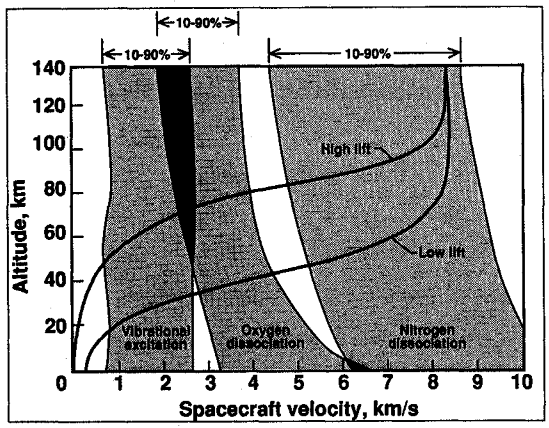

Fig. 4 Flight paths for high- and low-lift vehicles in the lower atmosphere.[16]

A complex combination of gas-surface collisions and chemical processes is known to excite molecules in the gas near vehicle surfaces. The decay of these excited states produces light emissions that have been observed in the vicinity of the Shuttle vertical fin and on other orbital spacecraft.[18] These emissions have been observed in the ultraviolet, visible, and near infrared. The likely excited molecular species include OH, CO, NO, and NO_2. For the Shuttle glow, the most intense region occurs in the red (approximately 700 nm).

The distribution of the neutral gas density, ion temperature, and composition; ion density, its energy, and composition; electron density and energy; excited molecules and their photon emissions; and the electric and magnetic fields are all substantially changed near the spacecraft. The characterization of these changes and the extent to which they extend into the local atmosphere should be thoroughly investigated.

Surface Effects—Aerothermodynamics

The effects on spacecraft surfaces come from the interaction of the high-velocity gas, ions, and electrons with the surfaces. The complex molecular interactions lead to surface heating, gas adsorption and desorption, excitation, and chemical changes of the gas on surfaces. These effects lead directly to degradation of most surface materials, particularly in the presence of atmospheric atomic oxygen. Ions and electrons interacting with the vehicle cause surface charging[19] that can lead to currents through the spacecraft, discharges, and interference with and damage to sensitive instruments and electronic packages.

Above 130 km, the gas arriving at the surface is substantially unaffected freestream gas. The collision frequency in the higher density gas layer around the vehicle is low enough that the freestream gas is not affected before surface collisions. Heating rates are low enough that they do not drive vehicle thermal design. Collisions with the surface have enough energy to excite and dissociate freestream molecules. The residence times on the surface are large enough to allow chemistry to occur. Indeed the surface can act as a third body, allowing chemical reactions to occur that are not probable in the gas. Chemical combinations of O and N from the gas phase and C (from the material) and H (from water) from the surface will exist on the surface and can desorb into the gas phase. These chemical effects manifest themselves in two important problems faced by spacecraft designers: spacecraft glow[18] and O degradation of surface materials.[20]

Below 130 km, a substantial buildup of gas occurs at the surface in the flow direction. As a result the freestream gas cannot reach the vehicle surface without colliding with other gas phase molecules, releasing energy to these molecules and significantly heating the gas. This hot gas transfers its energy to the surface, heating the surface to high temperatures. N_2 and O_2 dissociate in the gas, arrive at the surface as atoms, and can combine with themselves, other gas phase atoms adsorbed on the surface, and other surface species such as C (from the material) and H (from water). This molecular recombination can be a major surface heating mechanism. An ion sheath develops in the flow around the vehicle at altitudes between 95 and 125 km, which causes surface charging and radio communication problems. These heating, charging, and communication effects must be considered in vehicle design.

Instrumentation

The purposes of the downward-deployed tethered missions are to determine 1) atmospheric and aerodynamic effects in the vicinity of the tethered satellite and aerothermodynamic effects on its surface, and 2) the dynamics of the tether and its endmass, the satellite. This paper will concentrate on the former. Instrumentation (accelerometers, tensiometers, etc.) and data analysis for tether dynamics are treated elsewhere[21,22] and are not considered within the scope of this paper. It should be noted that the analysis of this dynamic data gives satellite drag that can be used to infer atmospheric density and temperature. (This technique is not discussed in this paper.) These inferences could be useful in interpreting atmospheric, aerodynamic, and aerothermodynamic data.

Both in-situ and remote sensing techniques can be applied to measuring flowfield and surface parameters on and around tethered satellites. To describe both freestream atmospheric and vehicle disturbed parameters completely, sampling should be made throughout the flowfield up to at least a satellite body diameter away from the surface (see Fig. 3). For the in-situ measurements this will probably require sampling booms. Measurements should also be made at a number of points on the satellite surface to characterize the effects of gas-surface interactions on the spacecraft. No attempt will be made to give experiment design considerations. This paper is limited to the discussion of existing instrumentation that could form the basis for future experiment design. Instrumentation includes mass spectrometers and other density measuring devices; plasma devices such as Langmuir probes and other electrostatic analyzers; optical spectrophotometers; magnetometers; and surface devices such as thermocouples, heat transfer transducers, O flux density sensors, etc.

Mass Spectrometers—Other Density Sensors

A number of flight mass spectrometers have been flown to measure constituent density in the lower thermosphere. These include the open source neutral mass spectrometer flown on the Atmospheric Explorer Satellite[23] and rocket probe mass spectrometers[24] flown during the Energy Budget Campaign. There have been a number of review articles[25,26] on the Atmospheric Explorer and Energy Budget Campaign from which a more detailed reference list can be obtained. Recently, a rocket probe experiment[27] to measure N_2 and Ar was reported that covered the altitude range between 90 and 130 km. Typically, satellite and rocket probe mass spectrometers weigh less than 10 kg and require less than 15 W average operating power.

These mass spectrometers and other density sensors offer a base from which aerothermodynamic and atmospheric experiments on tethered satellites can be developed. Aerothermodynamic experiments are different from atmospheric science experiments in the sense that a distribution of the flowfield parameters is needed for each time and space point as opposed to a single atmospheric data point. (In the atmospheric science case, the effects of the vehicle are considered a data analysis complication.) To measure density distribution, an articulated sampling probe (arm), designed to minimize gas flow effects, is required to survey the entire volume around the spacecraft. For spacecraft that have attitude control systems, the survey may be made with a boom that is not articulated but is extendable and retractable. For the spacecraft flowfield results given in Fig. 3, a sampling probe with a maximum length equal to or exceeding a body diameter (where the ratio of affected gas density to freestream gas density, in the forward direction, is less than 2) would allow density measurement to be made throughout most of the disturbed gas and at the boom's full extent would allow the accurate measurement of freestream density. Another consideration is the high density at altitudes below 150 km, which will require gas reduction methods as part of the mass spectrometer system. Also, O and O_2 (major atmospheric constituents) are highly chemically reactive and can cause degradation of the hot cathode in the mass spectrometer ion source (low emittance/power coated cathode will be required). These highly reactive gases are difficult to measure accurately since they recombine and form molecules that are associated more with gas-surface interactions than gas phase density. Proper sampling of this highly reactive gas near the satellite is required. Techniques used in the past include transparent seminude ion sources embedded in the flow, cyrogenic cooling of the ion source and satellite surfaces, and molecular beam techniques. Ion gauges have also been used to measure total density in the lower thermosphere; however, these gauges are gas composition sensitive and their use is generally restricted to altitudes below 110 km where the composition is less variable. These gauges are small in physical size, are less complicated, can be operated at much higher density, and require much less power than mass spectrometers. Ion gauges were flown during the Energy Budget Campaign,[26] and one is proposed to measure satellite orientation on tethered satellites.[28] Typical weight for flight ion gauges is 1 kg, and they require less than 2 W average operating power.

Recently, an ion trap mass spectrometer[29] that is similar to an ion gauge in size and complexity has become commercially available (see Fig. 5). Ions are trapped in the ion source by a quadrupole electric field and extracted for analysis by mass. This mass spectrometer[30] is simple to construct, is small in physical size, has high mass resolution ($m/\Delta m = 75$), and can be constructed with transparent grids to operate embedded in the flow to altitudes as low as 105 km.[31] The flight development of this instrument should be considered for density measurements on tethered satellites. Estimated weight and power consumption are less than 2 kg and 2 W, respectively.

Electron beam fluorescence[23] could be used to measure or infer the density distribution in the flowfield near tethered satellites. The application of this technique should be thoroughly investigated since the need for instruments on probes is eliminated, and a spectrophotometer that is needed to measure the fluorescence will probably be included in the spacecraft instrumentation package to measure vehicle and atmospheric glow. (See this paper's section on optical spectrophotometers.)

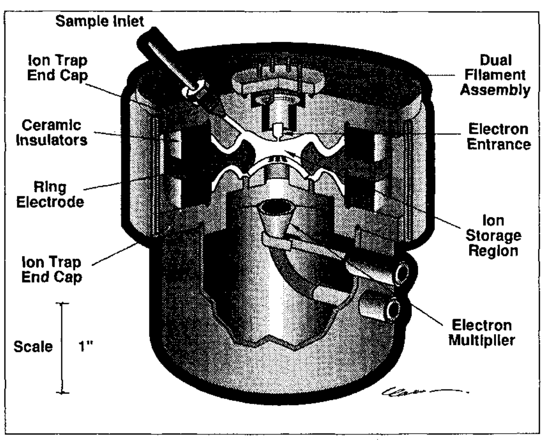

Fig. 5 Ion trap mass spectrometer.[29]

Plasma Instrumentation

There are a number of instruments that have flown on both satellites (Atmospheric Explorer and Dynamic Explorer) and rocket probes (Project Condor) to study ion and electron concentrations and electric fields. Further, TSS-1 contains several of these instruments[33] to determine electric field structure and charged particle constituent density and temperature in the vicinity of the satellite. The instruments on these missions included ion mass spectrometers to measure ion constituent density; retarding potential analyzers to measure total ion and electron density and energy distribution; and multiple probe systems to measure electron density distribution (i.e., Langmuir probes) and electric fields. Again, it should be noted that the distribution of parameters in the vicinity of the satellite is required to understand the complex nature of the ion and electron flow in the presence of charged surfaces and the ambient and disturbed electric and magnetic field.

Ion mass spectrometers have been flown on both satellites[34] and rocket probes[35-37] to measure ion constituent density. The previously mentioned review articles[25,26] also give a more complete reference list for ion mass spectrometers. An ion mass spectrometer is basically a neutral mass spectrometer without an ion source. Most of the comments on neutral mass spectrometers (see this paper's section on mass spectrometers—other density sensors) apply to ion mass spectrometers. An exception is that sampling problems are less complicated since ambient ions can be controlled with electric fields before analysis. The ion trap mass spectrometer (previously mentioned) should be investigated for possible use as an ion constituent density measurement device. It should be noted that other plasma devices discussed in the rest of this section are total ion detectors and cannot discriminate ion species.

Retarding potential analyzers have been used in flight[38,39] to measure total ion and electron density and energy distribution. This device is basically a gridded cylindrical cavity, simple to construct and small in physical size, and requires minimum operating power. Retarding potential analyzers have been used in conjunction with neutral mass spectrometers to separate the high-velocity freestream gas from lower velocity surface collided gas and have also been used on ion mass spectrometers to obtain constituent ion energy distributions.[40]

Probes on booms, to minimize the effect of central body potential, have had extensive use in space flight. On Dynamic Explorer (DE), Langmuir probes routinely provided fast response (2 sample/s) electron density and temperature measurements.[41] Further, the frequency and current of an extended antenna, as used on Project Condor,[42] were measured, from which electron density was derived. The electric field instrument[43] on DE, which consisted of symmetric double probes mounted at the end of booms, provided data on both the dc and ac electric fields. An ion drift meter[44] on DE gave the east-west components of total ion drift velocity. These and other electrostatic devices as a class are in general relatively simple, are small in physical size and weight, and require low operating power.

Optical Spectrophotometers

Most spectrophotometric measurements that have been made with instrumentation onboard rockets or satellites have been used for long-range sensing of emissions from atmospheric species[45,46] and to study airglow and the aurora. One interesting exception is an experiment containing a uv monochromator with a light source mounted on a boom extending from a rocket. This experiment, designed to measure O atom density by resonance fluorescence, has been flown on several rockets.[47] The data[48] from these flights are found to be in good agreement with the Mass Spectrometer Incoherent Scatter Thermospheric Model, MSIS-86.[49] A newly proposed experiment involves an Ebert-Fastie spectrophotometer (see Fig. 6) that was developed for AFE.[50] This instrument has a 0.6 nm resolution, weighs about 3.5 kg, requires less than 30 W of operating power, and is designed to measure the total radiation produced by the vehicle in the visible and ultraviolet regions of the spectrum.

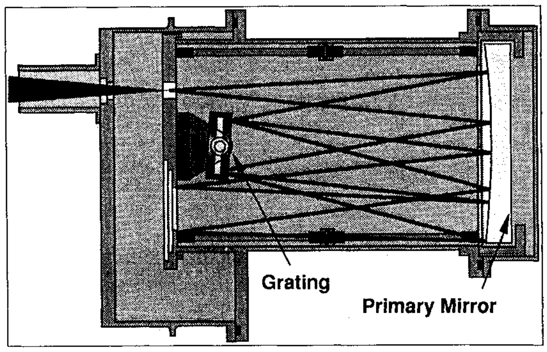

Fig. 6 Ebert-Fastie spectrophotometer.

Spectrophotometric observations of excited species produced by the interaction of a vehicle with atmospheric gases have been made on both the AE satellites[51] and the Shuttle[18] (the Shuttle glow phenomenon). In each case, the resolution and spectral range of the instruments was not sufficient to identify conclusively the species producing the emission (the highest resolution was 3.4 nm on the Shuttle). The resolution and spectral range available with the Ebert-Fastie spectrophotometer described earlier would substantially improve these measurements, but it does not have the resolution to identify fully the species produced both during satellite descent and orbit. There are small, lightweight spectrophotometers that are commercially available with high resolution (0.06 nm) in the required spectral range. The flight development of these spectrophotometers would allow identification of the species that are producing the light emission as well as the energy state from which the light is being emitted. These measurements would allow the extent of energy accommodation on the surface, the chemical reactions that take place on the surface, and the overall energetics of the surface-gas interactions to be determined.

Magnetometers

Magnetometers have been flown from the beginning of the space age to measure the terrestrial magnetic field in orbit. A number of satellites (DE-2,[52] S3-3,[59] and AE-C[54]) have contained magnetic field measuring instrumentation. The Magsat satellite was dedicated to sophisticated magnetic field measurements and successfully measured the magnetic field in the upper atmosphere. Magsat instrumentation[55-57] included both absolute sensors that sense the magnetic field effects on the frequency of atomic transitions (Zeeman effect) and relative measurement devices that use multiple nulled reference coils to give magnetic field magnitude and direction.

These flight magnetometers offer a base[58] from which directional magnetic field measurements can be made on tethered satellites in the lower thermosphere. Deep in the ionosphere, the magnetic field in the vicinity of the satellite can be driven by atmospheric currents and vehicular effects due to the flow of ions and electrons around the spacecraft. The separation of these magnetic field effects into their components using both instrument and data analysis techniques should be a major consideration for magnetic instrumentation on low-altitude tethered satellites. To properly analyze magnetic field data, the satellite position must be accurately known, the electric field (ion and electron concentrations) in the vicinity of the spacecraft must be measured, and the satellite magnetic signature must be known or nulled during testing and calibration. Magnetic field measurements should be made through the plasma sheath near the vehicle. The extent of the disturbed magnetic field can be substantial; as an example, the Shuttle plasma sheath is estimated to extend to 400 m forward, 1.5 km aft, and 0.5 km normal to the flow.

Surface Instrumentation

Instrumentation to measure the effects on surfaces embedded in a high-velocity, chemically reactive gas that contains free ions and electrons can be divided into a number of classes. These include sensors and measurement techniques to determine the following: surface temperature, heat transfer, and pressure; gas adsorption on surfaces, chemistry with other gas molecules and surface material, and desorption from the surface; and surface charging.

Thermocouples and heat transfer transducers have found extensive use in measuring surface temperature and the transfer of energy from the gas to the spacecraft surface and are included in the design of most spacecraft. Figure 7 shows proposed locations for heat transfer transducers on the TSS-AVM mission being studied by NASA and Martin Marietta.[2] These devices will be used to determine surface heat transfer distribution at altitudes as low as 110 km. For an altitude of 120 km, the surface temperature can reach values as high as 700 K at the stagnation point. (See Fig. 7 in Ref. 2.) The surface temperature distribution can also be used to determine satellite orientation. Orientation-sensitive high-pressure ion gauges[28] mounted on the surface at a number of locations have been proposed to measure surface pressure and to give inputs to vehicle attitude control systems. For the most part, gas adsorption and desorption and gas chemistry on spacecraft surfaces have been inferred from other measurements such as the interpretation of the source of Shuttle glow[18] and the modeling of temperature and heat flow measurements upon Shuttle reentry.[59] Direct measurement of the net result of this chemistry has been obtained from materials exposed to space environment in the Shuttle bay[60] and samples retrieved from the Long Duration Exposure Facility (LDEF).[61] Velocity distributions of oxygen atoms were also estimated by examining etching patterns of surfaces exposed to the flow on STS-8.[62] The above measurements depended on retrieving the experiment and estimating the O flux density, which was not measured. Recent development of small, lightweight, low-power O flux density sensors (see Fig. 8)[63] will allow O flux density on the satellite and tether surfaces to be measured directly. Sputtering of surface material by ambient ions has been observed[34] in flight mass spectrometers and should be investigated as a possible inflight surface analysis technique. Surface charging of the satellite affects the plasma measurements that have been discussed and influences the surface chemistry. Both the magnitude of the surface charge and its sign must be measured. The negative potential of rocket payloads has been determined by electrostatic analyzers that measured the cutoff of the ion energy spectra of ions interacting with the rocket surfaces.[64] A similar cutoff for electrons does not seem to exist either in rocket payload measurements[65] or in the Shuttle measurements.[66] A number of the electrostatic analyzers outlined in the Plasma Instrumentation section of this paper could be used (modified) to measure surface charge.

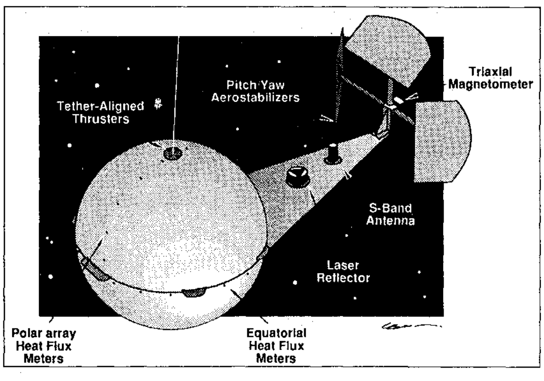

Fig. 7 Location of heat transfer transducers on the proposed TSS-AVM.[2]

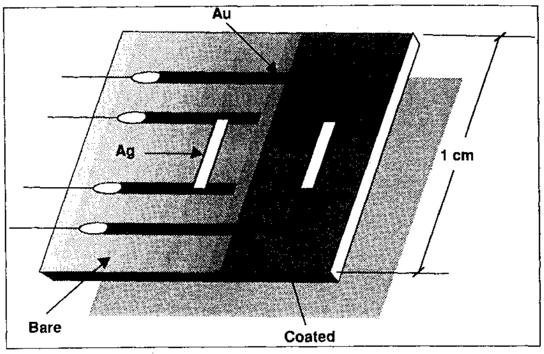

Fig. 8 Atomic oxygen flux density sensor.[63]

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