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TETHERED ATMOSPHERIC/IONOSPHERIC RESEARCH SATELLITE (AIRSAT)

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Abstract

An interdepartmental class of engineering students at the University of Michigan has designed a conceptual tethered research satellite mission to explore the Earth's upper atmosphere and lower ionosphere. Following the precedent set by the successful flight demonstration of the Small Expendable Deployment System (SEDS), it will be launched as a secondary payload aboard a Delta II rocket. The AIRSAT sub-satellite, connected to the orbiting Delta II with a 60 km tether, will collect information concerning electron density and temperature, ion concentration and relative ion temperature, sub-satellite surface pressure, acceleration of the sub-satellite, tether tension, attitude stability, and orbital decay in the altitude regime of 160 - 120 km. The sub-satellite is designed to operate down to 120 km where the tether is then cut. The design is innovative in concept and emphasized not only low cost but also a rapid transition from design completion to flight.

Introduction

The *in-situ* exploration of the Earth's lower thermosphere and ionosphere has been slow and difficult. This altitude regime is too high for aircraft and balloons and, due to atmospheric drag, too low for extended operations by satellites. Consequently, research of this region and the development of aerospace vehicles capable of operating under these conditions is a formidable challenge.[1] Yet, exploration of this regime is critical to understanding the near-Earth environment that is responsible for the majority of solar energy absorption and nearly all of the energy transferred from the solar wind through auroral processes.

To address this issue, the AIRSAT research group was asked to develop a complete proof-of-concept mission to evaluate and demonstrate the use of tethered satellite technology for remote exploration of the Earth's upper atmosphere and lower ionosphere as well as to conduct transition flow flight research. The mission parameters emphasized low cost, simplicity and rapid turn-around from design to flight.

To significantly lower the overall cost, the mission is based on the secondary payload concept; the AIRSAT system will be transported into space mounted on the second stage of a launch vehicle carrying a separate primary payload. The capability for this type of design has previously been developed and demonstrated by NASA using the Delta II 7925 three stage rocket whose primary payload is a NAVSTAR Global Positioning System (GPS) satellite. With this as a precedent, AIRSAT is designed to be launched aboard a Delta II although the design could easily be modified for other launch vehicles such as the Titan II, Minuteman II, or Pegasus. Figure 1 shows the second stage of the Delta II proposed for use in this mission.[2]

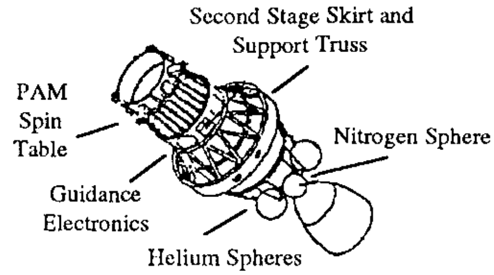

Figure 1. Delta II Second Stage

On the Delta II, there are four identical secondary payload envelopes mounted on the guidance section of the second stage. The mounting locations are on a ring surrounding the guidance equipment, but still within the fairing.[2] A typical secondary payload envelope on the Delta II is shown in Figure 2.

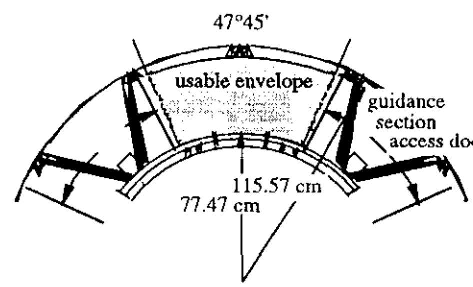

Figure 2. Secondary Payload Envelops on Delta II

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A side view of the Delta II payload, as shown in Figure 3, demonstrates the mounting of the AIRSAT platform on the Delta II second stage.[2]

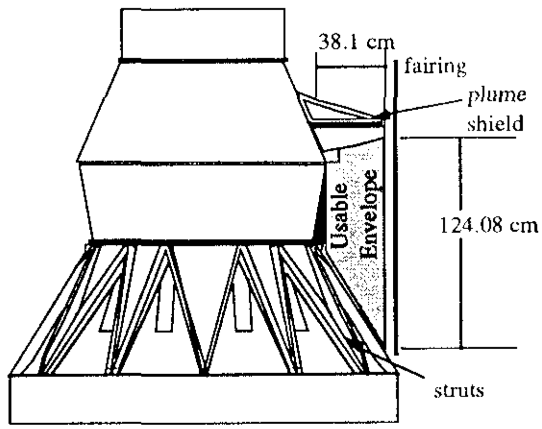

Figure 3. Side View of Delta II Second Stage

These mounting locations present a challenging packaging task for the AIRSAT system, and present many design constraints. The AIRSAT system maximizes the Delta II secondary payload capability in both mass and volume and utilizes all four available sectors.

AIRSAT Experiment Sub-satellite

The AIRSAT experiment sub-satellite design which best fulfilled all the mission requirements while meeting the constraints imposed by the Delta II secondary payload capacity is shown in Figure 4.

Figure 4. AIRSAT Experiment Sub-satellite

It consists of a circular ellipsoid (saucer-like) capsule and a pair of stabilizer wings that are mounted on a boom behind the capsule. The tether is attached to the top of the sub-satellite, above the center of mass. There is also a keel attached below the capsule to aid in roll and pitch stability. Figure 5 provides a side view of the sub-satellite, in its fully deployed configuration, showing the dimensions of the proposed sub-satellite.

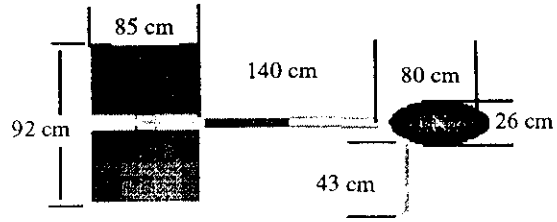

Figure 5. Side View of Sub-satellite

The capsule contains electrical and communications devices that support the various measurement instruments mounted on and through the surface of the sub-satellite. All internal equipment is attached directly to a framework which is made of an aluminum "T" section. The framework is bent or machined to follow the elliptical contour of the capsule and laid out in a radial pattern. All external components, such as the boom, the tether connection, and the keel, are also connected to the frame through the skin.

A telescopic boom connects the wing stabilizers to the main capsule. The boom needs the extra complication of a telescoping mechanism to be both short enough to fit in the allowed secondary payload volume and long enough to provide a good moment arm for the stabilizing wings. The wing system consists of two vertical wings, each divided into two sections. Each section consists of a frame of aluminum rods that support a thin aluminum sheet. The multiple wing sections allows for a folded configuration that will fit within one of the secondary payload areas. In deployed position, the two vertical wings are set apart by a cross beam so they will not be in the aerodynamic flow 'shadow' of the capsule.

The keel consists of an aluminum rod and endmass that aid in the stability of pitch and roll by lowering the location of the sub-satellite's center of mass. As with the boom and wings, the keel is folded to fit within the payload area.

Prior to ejection from the second stage, each component unfolds itself. All of the eight movable mechanical joints are spring loaded. The springs store enough potential energy to provide the momentum to unfold the components and lock them in place. The joints are designed to provide the desired motion and locking mechanism to secure each component's position, as well as to aid in the unfolding.

The sub-satellite's frame and skin are made of aluminum. It's ease of fabrication, low cost, and low density make it a desirable aerospace material. The external sub-satellite surface is also required to maintain good electrical conductivity for atmospheric measurements. To satisfy this constraint, the class suggested an outside surface coated with aluminized Teflon to both reflect solar radiation (to reduce heating) and to maintain electrical conductivity. A conductive paint similar to that used on TSS-1 , if it's high temperature characteristics were found to be adequate, could also be utilized.

Some components inside the sub-satellite, such as the battery, must be protected from excessive heat. Most of the heat will come from skin friction with the atmosphere, and most of that is at the leading edge of the sub-satellite. To insulate the interior, a polyimide (PI) resin is placed inside the skin. This material has a favorable combination of thermal stability, processibility, structural reliability, and long service life. The insulation is tapered from a thick layer at the leading edge, to a thin layer at the trailing edge.

AIRSAT Tether Specifications

Table 1 lists the general specifications of the tether proposed for use in the AIRSAT mission.

Table 1. Specifications for AIRSAT Tether

Parameter	Design
Type:	Non-conductive
Length:	60 km
Diameter:	1.3 mm
Mass:	~95 kg
Material:	B29/12 x 1500 Kevlar
Construction:	Multi-layer and braided
Jacketing:	None required

The overall requirements for the tether are extremely severe considering the upper- and lower-altitude environments. The most important characteristics required for the 60 kilometer long tether, with the lower end at a 120 km altitude include:

- High strength-to-weight ratio
- Maximum tension of 200 N
- Maximum mass of 90 - 120 kg
- Maximum diameter not to exceed 2 mm to minimize aerodynamic drag,
- Serviceability for temperatures ranging from -100° C to 400° C
- Ability to withstand the potential degradation of atomic oxygen flux ranging from 10^{18} to 10^{21} atoms/m^2-hr over the duration of the mission; and
- Effective protection against solar ultraviolet radiation.

The material that adequately met each of these criteria was the Aramid fiber with the brand name KEVLAR - 29. Kevlar has strength characteristics superior to stainless steel, has low density, and can be braided to provide flexibility with low torque. It can be impregnated to provide good resistance to abrasion and protection against ultraviolet damage and can be manufactured to AIRSAT's desired length, making splicing unnecessary.

According to the research completed at Martin-Marietta, the duration of the mission (8-30 hours) is too small for atomic oxygen to have a detrimental effect.[3] Of larger concern is the temperature range the tether is likely to experience. However, the manufacturer of Kevlar-29 has indicated that temperature will not be a problem since Kevlar has proven resilient to both low and high temperatures.

Another concern for the tether was the possible damage or severing of the tether by micro-meteoroids. If a solid strand of Kevlar were to be used, any damage caused by the micro-meteoroids would be critical and could cause the tether to fail. However, if a tether consisted of braided Kevlar there would be no matrix to transmit a fracture stress to other filaments in the braid. The AIRSAT tether would have to have enough filaments to ensure that it would not fail during the experiment. There are two structural changes that can strengthen the tether. One is to use a lager number of strands of smaller denier, such as 48x200d. The filament size and strength are the same as fewer strands and larger denier, but a local break will allow the finer braid to close in and retain a higher percentage of original brake strength. The second method is to use a successive number of layers, called braid-over-braid, to allow outer layers to act as buffers. In the case of the AIRSAT tether, it would be wise to employ both methods to ensure that the tether does not break prematurely. Manufacturers recommend that designers should allow a safety factor of three of four when determining how much Kevlar to use. The tether the AIRSAT mission will be using is at least 6 times as thick as needed.

Mission Timeline

The Delta II three stage rocket will be inserted into an elliptical orbit upon launch and will undergo first stage burnout and fairing separation. Next, the third stage will separate and carry the primary payload to it's prescribed orbit. Once this maneuver has been completed, the AIRSAT mission will begin. By utilizing fuel margins and the attitude control capabilities of the second stage of the Delta II, the rocket will be transferred from the initial elliptical orbit to a circular orbit appropriate for the AIRSAT system. Any fuel that remains will be burnt off in a final depletion burn. During this burn, the second stage will be oriented such that the velocity impulse imparted to the system will produce only a slight increase in the orbital inclination angle; the orbit will remain circular.

The next stage of the mission is the ejection and deployment of the sub-satellite. The second stage will be oriented so that the sub-satellite is facing downward toward Earth. From this position, the sub-satellite is ejected from the launch vehicle and the attitude control system will reorient the second stage so that the tether canister and deployment mechanism are lined up with the deploying tether. Over the next five hours, the sub-satellite will be deployed toward the Earth. Throughout deployment, until the attitude control fuel is exhausted, the attitude control system will be used to stabilize the second stage. As the system enters the atmosphere, the sub-satellite will experience aerodynamic drag forces causing the orbit of the system to decay into the atmosphere over the next 8 to 30 hours.

Throughout the deployment (215 to 155 km) and operational periods (155 to 120 km), the sub-satellite will be taking scientific measurements of the atmosphere and ionosphere, and measuring transition flow flight characteristics as well as tethered satellite characteristics with its array of sensors. The data will be transferred from the sub-satellite to a computer in the second stage, and from there to ground stations via microwave telemetry links. When the sub-satellite reaches 120 km the orbital decay will be very rapid, so the tether will be released from the second stage. The sub-satellite and tether will quickly descend and burn up in the atmosphere while the second stage will remain in orbit to transmit the remaining data from the computer's memory. Table 2 shows the expected mission timeline.

Table 2. Expected Mission Timeline

Time	Action
0 seconds	Launch
260 seconds	Delta II First Stage Burnout
380 seconds	Delta II Faring Separation
1267 seconds	Delta II Third Stage Separation
4473 seconds	Circularization/Depletion Burn
4533 seconds	Sub-satellite Ejection
8 - 24 hours of deployed operation	
Second stage decays to 175 km - tether is cut; sub-satellite and tether re-enter	

Sub-satellite Launch Mechanism

The deployment of the tethered satellite from an orbiting platform relies on the ability of the sub-satellite to pull the tether out of its storage canister. However, when the sub-satellite is close to the platform, the force from the gravity gradient is too small for the sub-satellite to pull the tether. Therefore the sub-satellite must be accelerated away from the platform in order to initiate the deployment of the tether. If the 105 kg sub-satellite is accelerated to 3 m/s, it will have enough momentum to separate the sub-satellite and platform such that the gravity gradient can provide sufficient force to pull the tether the rest of the way. A novel ejection mechanism concept was developed to provide this initial energy.

The ejection mechanism utilizes a spring loaded extendible boom structure. The boom extends to 5 meters, from an initial folded configuration of 10 centimeters. As the ejection boom extends, the springs in the joints of the boom transfer 157.5 kg-m/s of momentum to the sub-satellite, driving it away from the platform. Since the acceleration is spread out over 5 m, the acceleration on the sub-satellite is far gentler than a single acceleration impulse. The sub-satellite itself has a boom and wing structure that could be damaged by very strong acceleration. The momentum of the sub-satellite from the spring loaded boom is augmented by 157.5 kg-m/s from a compression spring situated in the center of the boom. This compression spring initiates the ejection process and increases the momentum of the system to a total of 315 kg-m/s. The sub-satellite ejection scenario and second stage rotation is shown as a series of time sequenced sketches in Figure 6.

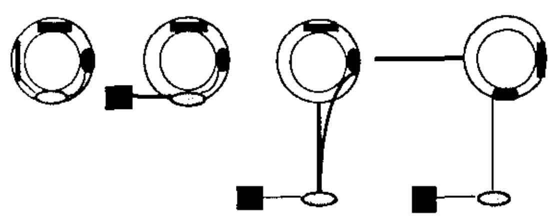

Figure 6. Sub-satellite Ejection and Deployment

The ejection boom has another advantage besides the gentle application of energy to the sub-satellite. The boom will hold the sub-satellite in a relatively fixed attitude as it is ejected. This should minimize 'tip off' tumbling of the sub-satellite as it begins its deployment. If tip off is excessive, the sub-satellite could become tangled in the tether.

The ejection boom is designed as a series of 10 rings, connected together by 51 jointed linkages. Three evenly spaced linkages connect adjacent rings. The linkages are staggered so they will store compactly in the folded position. Each linkage has a torsion spring in its joint that provides the energy to extend the boom and eject the sub-satellite. A small section of this ejection boom has been prototyped.

Dynamics and Control

The accuracy of the data collected and the success of the mission is dependent upon the system being in a stable configuration at all times. In addition, the orbit of the system must provide accurate ground coverage whereby all information gathered can be successfully transmitted to Earth.

To model the system, a dumbbell model was used which assumes the Delta II and the sub-satellite can be considered point masses in relation to the system as a whole, the tether curves or deflects under the influence of atmospheric drag, and all out-of-plane disturbances are small when compared to the in-plane motion of the system. This model is shown in Figure 7.

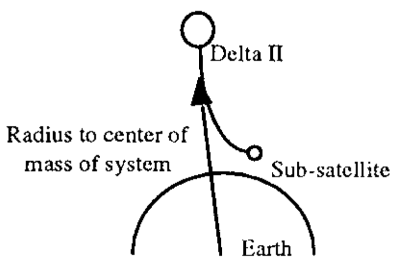

Figure 7. AIRSAT system Model

The dumbbell model is designed to allow the motion of the center of mass of the system to represent the motion of the entire system which drastically simplifies the analysis of the mechanics and dynamics of the problem.[4]

The orbital motion is highly coupled with the rotational motion of the AIRSAT system. Therefore, the behavior of the tether is related to the orbital angular motion. In theory, the relationship between the tether motion and the orbital motion makes it almost impossible to have equilibrium positions in an orbit unless changes in the orbital angular motion are zero. In an elliptical orbit, the orbital angular motion changes with position on the orbit. However, in a circular orbit, the orbital angular motion is constant making it possible for the system to attain equilibrium. Therefore, the orbit selected for the AIRSAT mission will be a circular orbit with an inclination of approximately 32 - 34 degrees.

The second stage of the Delta II is left in an elliptical orbit with an inclination of approximately 32 degrees after third stage separation. Since inclination change maneuvers are costly in terms of fuel consumption, the second stage will remain at that inclination. However, several orbit transfers (requiring velocity impulses) will be used to transfer the orbit to the more desirable circular orbit. The first transfer burn will occur at the apogee of the initial orbit and will have a magnitude of 3.03 m/s acting in the opposite direction of the incidental velocity vector; this slows the second stage. The effect of this impulse will be to place the second stage in a transfer ellipse coincident with the desired final orbit.

The second velocity impulse occurs at perigee of the final orbit, that is, at an altitude of 215 km. The second impulse has a magnitude of 151.34 m/s also opposite to the current velocity vector and will produce the desired circular orbit at the correct altitude. The total velocity impulse needed to circularize the orbit is 154.37 m/s. Finally, a depletion burn will occur to deplete any excess fuel that remains. This burn will act only to produce a slight increase in the inclination of the orbit.

The effects of the atmosphere on the system, aerodynamic drag and orbital decay, were also explored to consider their impact on the design of the system. The predicted aerodynamic drag on the sub-satellite as a function of altitude is shown in Figure 8.[5]

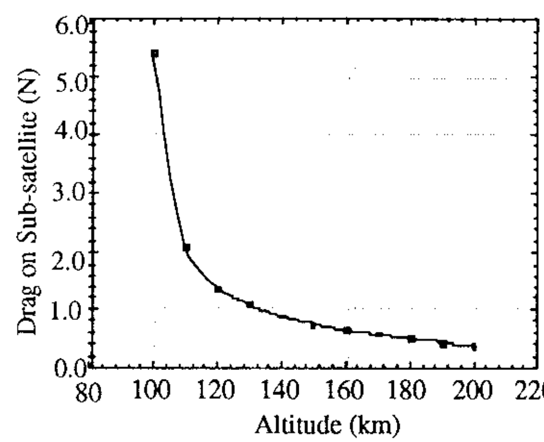

Figure 8. Aerodynamic Drag on the Sub-satellite as a Function of Altitude

The aerodynamic drag on the second stage is orders of magnitude smaller due to its higher initial altitude even though its effective surface area is at least twice as large.

The drag on the tether is an important issue in determining the dynamics of the system. To predict the maximum drag that the tether would be subjected to, the drag was computed at the center of pressure (where the drag force would be the largest) and integrated over the length of the tether. Although this value varies with altitude, in free molecular flow, the maximum drag is expected to be on the order of 11 Newtons. Figure 9 shows the drag on the tether per kilometer.

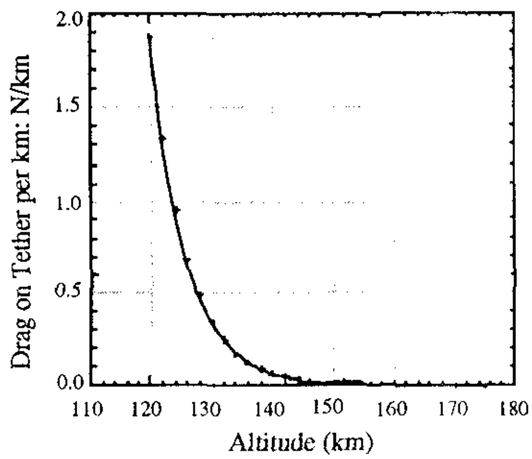

Figure 9. Drag on the Tether/kilometer

A 60 km tether will be used to deploy the sub-satellite downward into the Earth's upper atmosphere; the sub-satellite will be at an altitude of 155 km after the tether is fully deployed. The tether will be deployed using a length rate control law. [6]

$$\lambda' = \lambda + [\underline{k}]^T[\underline{x}]$$

where:

k = gain vector
x = state vector
λ = nondimensionalized tether length

Using this law, the tether will be deployed at exponential and uniform rates and the entire deployment procedure will take approximately 5 hours.

The orbital decay of the system is a direct result of the aerodynamic drag experienced by the components of the system. The initial sub-satellite altitude should be selected such that the mission duration would be 24-30 hours; the mission ends when the sub-satellite reaches 120 km and before the sub-satellite battery energy is consumed. However, this estimate depends on correct orbital altitude insertion and accurate orbital decay models. A calculated prediction of the minimum mission life is on the order of 13 hours. Additional analysis in this area is recommended.

Active and passive control systems will be used during the AIRSAT mission to provide stability and to perform some of the maneuvers required during the mission. The second stage of the Delta II has an active control system which will be used to provide stability, to rotate the rocket after the sub-satellite has been launched, and to circularize the initial orbit. Both active and passive control systems will be used to stabilize the sub-satellite. Attitude thrusters will be used when the sub-satellite is outside the atmosphere and a keel structure and the tension in the tether will be used to help provide stability in pitch and roll. When the sub-satellite is inside the atmosphere, a passive control system will be used. The passive system consists of wings attached to a boom, a keel structure, and a nutation damper. The wing configuration will provide stability in yaw, while the keel structure and tether tension will provide stability in pitch and roll. A nutation damper will be placed in the yaw plane to damp out any perturbations in the motion of the system in this plane. The attitude thrusters can also be used when the sub-satellite is in the atmosphere in case of any large perturbations in the motion of the system.

Scientific Research

The mission of AIRSAT is to make fundamental ionospheric and atmospheric measurements, observe aerothermodynamic phenomena on a satellite in the transition region, acquire data which specifically describes the dynamics of a tethered satellite system (proof-of-concept measurements), and to help determine how the tethered satellite concept can be applied to scientific and engineering research in the near earth space environment.

Due to mass, volume, and cost constraints in this first AIRSAT mission, the number and type of sensors is limited. For measurements of the natural environment, the primary focus is on ionospheric sensors, only requiring neutral gas measurements to characterize the immediate environment surrounding the sub-satellite. Based on the results of this first mission, it would be possible to provide a new instrument complement which emphasizes the neutral atmosphere characterization.

The ionosphere is made up of a diffuse plasma. The electrons and ions do not necessarily have the same temperatures, so there will be different types of sensors to measure each one independently.[7] For electron temperature and density information, two Langmuir probes will be placed on the sub-satellite such that they are perpendicular to the velocity vector.

A retarding potential analyzer (RPA) will measure ion concentrations and average relative ion temperature. A complex grid system which varies with voltage allows ion collection at different rates depending upon the directed energy and mass of the particle. A two cm diameter orifice allows particles to enter the RPA for collection and is placed in the center of the leading sub-satellite surface heading into the ram direction. From these electron and ion I-V curves, fundamental ionospheric characteristics can be deduced.

Observations will be made to describe the aerothermodynamic behavior of the sub-satellite. These include measuring the surface heat transfer with heat flux sensors, sub-satellite surface pressure with ionization gauges, and total sub-satellite acceleration (3 axes) using miniature accelerometers. The tri-axial accelerometers within the sub-satellite will consist of three orthogonally-aligned sub-miniature linear accelerometers. Ideally, these three accelerometers should be placed at the center of inertia of the sub-satellite. However, due to the unusual volume constraints, this is not practical. Instead, acceptable results should be obtained as long as each accelerometer is only displaced from the center of inertia in a direction along it's sensitive axis. In this manner, vibration of the sub-satellite should not cause undue distortion of the acceleration signal.

Fourteen heat flux sensors will be used to measure the heat transfer to the surface of the sub-satellite. This will be done by differentiating the temperature between opposite sides of the sub-satellite skin. As heat is transferred through the surface, two thermocouple junctions will generate small voltages. The difference in voltages between the two junctions is interpreted as proportional to the temperature differential.

Twelve ionization gauges will measure the pressures experienced at different points on the sub-satellite surface. The Bayard-Alpert Gauge is a hot filament ionization gauge. The gauge is operated by bombarding and ionizing the gas in the gauge with electrons emitted from the heated filament. The resulting ion current collected by a collector anode is proportional to the ambient pressure in a gauge. Figure 10 shows the external sensor layout on the sub-satellite.

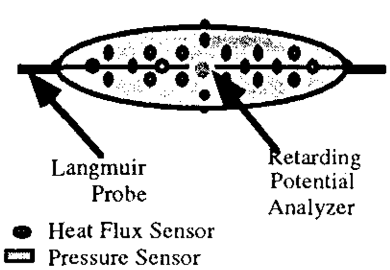

Figure 10. External Sensor Array (Front View)

Other observations will monitor the behavior of the second stage, tether, sub-satellite system. Two tensiometers provide tether tension information at the sub-satellite and the second stage. The tensiometer at the sub-satellite is made of three load cells sandwiched between two pressure plates. This also provides information on the angle which the tether makes with the sub-satellite axis.

The Global Positioning System (GPS) will be used to provide sub-satellite attitude information and general location. GPS operates by decoding precise microwave transmitted time-coded signals from various NAVSTAR satellites in high earth orbits (around 20,000 km). These signals are combined with knowledge of the orbital positions of the broadcasting satellites to triangulate the exact position of the receiving antenna. The GPS system can give very accurate attitude information by monitoring the phase differences between three different signals received at three non-collinear antennae placed at least 18 cm apart on the sub-satellite. Position of the sub-satellite can be measured to well below 100 m accuracy in the three directions. Additionally, three pairs of pressure sensors in an anemometer-type configuration will also provide attitude information while flying in the transition region. Figure 11 shows the internal sensor array.

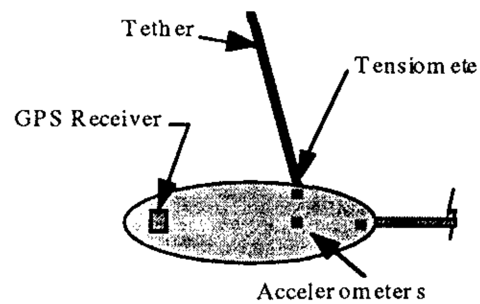

Figure 11. Internal sensor area of sub-satellite

Communications

The primary task of the communication system is to acquire the data from the sensors and successfully down link the information to ground stations. As suggested in Figure 12, the process begins with the sensors on the sub-satellite. [8,9]

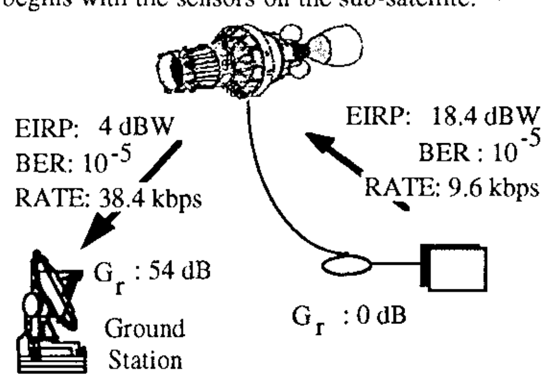

Figure 12. Communications Downlink Overview

The output is collected and processed for uplink to the second stage. The second stage then stores all the information into its memory where it is kept until it is transmitted to ground stations.

Due to the small size of the sub-satellite, the primary goal in the design of the communications systems was to minimize its mass and power requirements. Therefore, a direct link to Earth was dismissed because it required greater mass and power budgets within the sub-satellite. By first sending the data to the second stage, a distance no greater than 60 km, the higher powered system required for transmit to the ground can be placed on the second stage.

The sub-satellite to second stage link will operate between 2.2 and 2.3 GHz with a data rate of 9.6 kbps. This rate is sufficient for the sub-satellite sensor data rate. Once it arrives at the second stage it is put into the computer's memory after going through initial data processing. This on-board processing reduces total data per orbit required to be transmitted to the ground to 500 kbytes. The memory can hold 4 orbits worth of data (see Electrical Systems) with newly archived data over-writing the oldest stored data. The computer's memory is then continuously transmitted open-loop to ground stations on Earth. This link transmits at a rate of 38.4 kbps and assures that at least two orbits worth of data can be down linked while over one ground station, which is approximately six minutes of coverage. On the average AIRSAT will pass over a minimum of one ground station per orbit. This configuration allows 100% transmission of data.

The overall system was designed to have a bit-error-rate (BER) of 10^{-5}. This is equivalent to having ten error bits for every one million bits transmitted, resulting in a very reliable and accurate overall link. The Effective Isotropic Radiated Power (EIRP) of each link is sufficient to guarantee this BER.

Electrical and Computer Systems

Power is essential to the operation and proper functioning of the AIRSAT mission. In the design of a power supply, many factors were considered to insure the safe and reliable operation of the mission. A power source must fit within the mission constraints while providing adequate power to all of the systems. In addition, cost, reliability, equipment safety, size and weight must all be considered carefully. After analysis based on these criteria, the decision was made to use batteries as the power source for both the sub-satellite and second stage systems. Table 3 lists the specifications of the batteries chosen for the sub-satellite and second stage.

Table 3. Battery Specifications

	Sub-satellite	Platform
Chemistry	Silver/Zinc	Silver/Zinc
Cost	$20,000	$4,000
Nominal Voltage	29.6 V	28V
Capacity	4.1 kW-hr	7.0 kW-hr
Total Mass	33.6 kg	59.1 kg
Total Volume	23.4 L	24.7 L

Through research of commercially available qualified batteries, Ag/Zn batteries were chosen as the best fit within the mission's constraints while supplying adequate power. Two small - cell battery packs have been selected to provide power on the sub-satellite; with each cell providing 14.8V, a series combination provides a nominal voltage level of 29.6 V. At 140 A-Hr, this will provide a total power of 4.1 kW-Hr to all of the sub-satellite's internal systems. On the second stage, a single - cell Ag/Zn battery with a nominal voltage of 29 V will be used. It will provide 7.3 kW-Hr to all of the second stage's AIRSAT systems at an operating current of 250 A-Hr.

Not only must adequate power be supplied to all of the on-board systems, it must also be delivered reliably and efficiently. The design of a distribution system is as important as the source itself. Many of the systems requiring power need different input voltages, which must be accommodated by the distribution system. These voltages must be regulated to avoid line noise and voltage spikes which could hamper the operation of a system. Fault and surge protection must be employed to insure the reliable operation of the systems; a power failure in any system would render it inoperative, and as many of the systems are essential to the mission such a failure could cripple or even end the mission. Therefore considerable care must be put into the design of a reliable distribution system. Two main options exist for a distribution system: a centralized power source or a distributed architecture. The former uses a single voltage source and employs the use of DC/DC converters to provide the required voltage levels to the various systems, while the later relies on the use of multiple batteries at different operating voltages.[10] Pros and cons exist for each system, but after an analysis the decision was made to use a distributed power system.

In addition to the power supplies and distribution systems, a computer system must be used aboard the platform to perform control functions and data handling procedures. A microprocessor based computer is needed to process and store the experimental data being uplinked from the sub-satellite, and to control the communication of this data to the ground stations. In addition to the data handling, the computer will also be responsible for the timing/sequencing of the mission, primarily to control the operations and systems control during deployment. To meet these needs as well as conforming to the mass and size requirements as closely as possible, an Embedded Micro - Controller (model EPC - 22) from Industrial Computer Systems was selected as the best option. Operating at 25 MHz, this small computer system based on the Intel 386SL processor is capable of handling the required tasks.

Future Research

Future missions can build on the results of AIRSAT. Better knowledge of the lower ionosphere and upper atmosphere will improve the models used for design studies, not only for scientific research and future tethered satellite missions, but also for transonic flow flight research.

As a proof-of-concept mission, there are still some uncertainties involved that will require further study. Some of these uncertainties are:

- *Final inclination of the orbit:* The depletion burn that constitutes the final orbital maneuver in the mission will increase the inclination of the system by a small amount. The degree of inclination change will be dependent on the amount of fuel remaining after the circularization of the orbit, an unknown quantity. The inclination affects the ground station coverage for the communications equipment and is therefor important to the success of the mission.

- *Orbital decay rate:* The length of time in orbit depends on the energy loss of the tethered system. The mathematical models for the dynamics of a tethered system in a partial atmosphere are hindered by the fact that they have almost no empirical data to confirm or refine them. The duration of the mission depends on this decay rate.

- *Internal sub-satellite temperature:* Also as a result of the lack of empirical data, the internal temperature of the sub-satellite as it decays downward into the atmosphere cannot be closely predicted. As there is a specified range of temperatures at which the instruments in the sub-satellite will operate, this information is highly valuable.

Although these uncertainties all impact the mission, analysis of each of them indicates that if the worst case scenario were to occur, the mission could still be considered a marginal success in terms of the proof-of-concept guidelines outlined for the project.

Future tethered satellites can extend the work of this mission in the following ways:

- Use a polar orbit that will allow for global coverage of the Earth.
- Make measurements with instruments not included in the AIRSAT complement for logistics reasons. This could include neutral constituent and concentrations, sub-satellite surface erosion, and auroral studies.
- Test other sub-satellite shapes for their aerodynamic properties, especially for minimizing drag and increasing passive stability in thin atmosphere.
- Perform longer missions that can resist orbital decay by using thrusters on the orbiting platform. This would allow for mapping at nearly constant altitude for extended periods of time.

The AIRSAT system is a complete system, from launch to down linked data. Tethered satellites are a promising technology for exploring the Earth's upper atmospheric/ionospheric region and to conduct research into transition flow flight. Due to its simplicity and low cost, AIRSAT is an excellent way to prove tethered satellite technology as a science and engineering tool as well as a precursor for more complex and costly missions.

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This report summarizes the enthusiastic efforts of nearly 30 College of Engineering students from five departments at the University of Michigan. The complete description of AIRSAT and a class list can be found in the design class Final Report.[11]

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