SSC9-III-4

UW DAWGSTAR: ONE THIRD OF ION-F

An element of the Ionospheric Observation Nanosatellite Formation (ION-F)

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Abstract. The preliminary design for the UW Dawgstar nanosatellite is presented. The Dawgstar is a 13 kg satellite designed as a part of the University Nanosatellite Program funded by AFOSR, DARPA, AFRL, and NASA. The goal of this two-year program is to design, build, and fly nanosatellites. The mission overview is detailed, including the coupling with the University partners Utah State and Virginia Tech in the Ionospheric Observation Nanosatellite Formation (ION-F). The mission includes several formations and formation keeping experiments, and distributed ionospheric measurements. Each of the subsystems is also detailed, including the design and integration of eight miniature pulsed plasma thrusters for attitude control and formation flying.

Introduction

In the past, the general approach to satellite design consisted of mounting a large number of instruments and other science packages on a single support platform. While this method in general provides the capability for large amounts of data collection, it becomes extremely inefficient when one considers the overall costs due to design, construction, and implementation.

In response to the increasing need for a low cost, versatile science and communications platform the Air Force Research Laboratory (AFRL) initiated a program called TechSat21 that will demonstrate the feasibility of using distributed micro-satellite systems to do the work of a large, dedicated satellite platform [1]. Research regarding low cost nanosatellite technology is ideally suited for the university environment. In early 1998, the Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA) published request-for-proposal (RFP) that sought ten universities to take part in what is called the University Nanosatellite Program. The goal of this two-year program is to design, build, and fly nanosatellites.

Several universities, including the University of Washington (UW), were selected to take part in this program funded primarily by the AFOSR and DARPA. NASA has since joined the program and is providing additional funding and hardware assistance to university teams that are attempting formation flight experiments. Currently, the UW is teamed with Utah State University (USU) and Virginia Polytechnic Institute (VPI) to form a cluster of three nanosatellites called the ION-F, or Ionospheric Observation Nanosatellite Formation. The name ION-F also denotes the two operational goals of the cluster: ionosphere science measurement and formation flight.

For the last 6 months, the students in the AA420/421 capstone space design course have worked on the preliminary design of the UW nanosatellite, named the "UW Dawgstar." The primary goal of the ION-F cluster is to demonstrate the capability for formation flight; therefore the UW Dawgstar will have an active propulsion system. In order to complete the task of determining the preliminary design, the project was broken down into ten subsystems: Mission Planning, Structures, Payload, Propulsion, Attitude Determination and Control (ADCS), Power, Thermal, Guidance & Navigation, Communications, and Command and Data Handling (C&DH). This paper details each of these subsystems.

Mission Planning: Formation Flight

Definition of Formation Flight

The concept of formation flying satellites is frequently confused with that of a satellite constellation. As defined by the NASA Goddard Space Flight Center, a constellation is composed of "two or more spacecraft in similar orbits with no active control by either to maintain a relative position" [2]. Station keeping and orbit maintenance are performed based on geocentric states, so groups of global positioning system (GPS) satellites or communication satellites are considered constellations. In contrast, "Formation flight involves the use of an active control scheme to maintain the relative positions of the spacecraft" [2]. The difference lies in the active control of the relative states of the formation flying spacecraft. A distinction must also be made between formation keeping (referred to here as formation flying) and formation changes. Formation keeping is the act of maintaining a relative position between spacecraft in the presence of disturbances, while formation changing modifies the formation type, changing the relative satellite dynamics.

Relative positional control of multiple spacecraft is an enabling technology for many types of science requiring distributed measurement. Some of these uses include radar and optical interferometry, and distributed in-situ space science. The ION-F science mission of distributed ionospheric impedance measurements is an example of distributed *in-situ* space science.

Types of Formation Flight

There are three general cases of formation flight: leader-follower, same ground track, and side by side [3] Of these, the first two are the focus for the ION-F mission, primarily because of the limitations of the propulsion system in maneuvering to the side-by side formation. Therefore, the first two are discussed below.

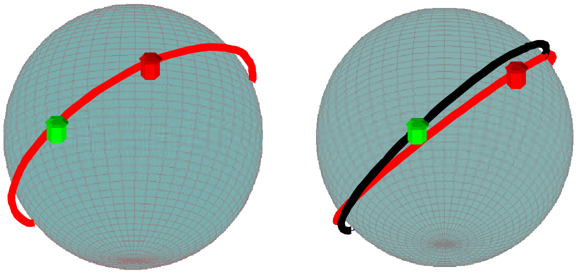

Fig. 1 Two formations being examined for the ION-F constellation: Leader-Follower on the left and Same Ground Track on the right.

The simplest configuration in which spacecraft can fly in formation is leader-follower, shown in Fig. 1. In this formation, the orbital elements of each spacecraft are identical except for the true anomaly, or the spacecraft follow the same orbital path at different times.

The same ground track formation (Fig. 1), termed "ideal" by NASA Goddard [2], is one in which two or more satellites have identical ground tracks. The leader-follower configuration described above does not produce identical ground tracks in any non-equatorial orbit due to the rotation of the Earth under the inertial orbital frame. It is possible under Keplerian conditions to define two circular orbits that create identical ground tracks at different times. Defining the orbits of the satellites requires the appropriate choice of the difference in the longitudes of the ascending nodes (ΔW), and the difference in the true anomalies (Δn) between the two orbits. The values of these quantities may be determined based on a desired time lag (Δt) between satellite passes over some point on the ground. Two equations and three unknowns govern the same ground track formation, thus fixing any one of the variables produces a viable formation. For an orbital radius (r) and gravitational parameter (m), the two equations linking these quantities are:

$$\Delta\Omega = \frac{2p}{86400}\Delta t \qquad (1)$$

$$\Delta n = \sqrt{\frac{m}{r^3}}\Delta t \qquad (2)$$

These two equations can be equated to produce equation (3), relating the difference in true anomaly to that in the longitude of the ascending node.

$$\Delta\Omega = \frac{2p}{86400}\sqrt{\frac{r^3}{m}}\Delta n \qquad (3)$$

Simulation overview

A computer simulation of the spacecraft dynamics and the formation-flying mission is being implemented in the Matlab®/Simulink™ nonlinear simulation environment. This simulation has three purposes:

1. To accurately predict the performance of the Dawgstar and the ION-F mission requirements.
2. To serve as a testbed for formation flying controller development.
3. To increase the probability of success of the complex formation flying mission.

The simulation is being developed in four stages, each described below, of increasing complexity. Phase 1 and elements of Phase 2 have been completed.

Phase 1

Phase 1 includes a dynamics model with accelerations due to drag and gravity. The drag is calculated using a simple density model, and gravity is determined using the J2 term of the gravitational potential [4]. Coordinate transformations are used to find the active spacecraft's position and velocity relative to the passive spacecraft. The Clohessey-Wiltshire (CW) equations of relative motion [5] are simulated and the results are compared with those of the geocentric dynamic simulation. Basic inter-satellite communication is enabled to allow for relative measurements.

Phase 2

The main goal of Phase 2 is to design a formation-keeping controller and close the loop with propulsive actuation. A formation keeping controller is developed to satisfy the leader-follower and same ground track formations. It is hopeful that the same controller will work for both formations because it will only reject disturbances from the stable orbits. The propulsion system is modeled as the micro-pulsed plasma thrusters being developed for the Dawgstar, namely on or off thrust at 0.14 mN. Additional dynamics such as solar pressure and lunar gravitation will also be integrated.

Phase 3

Phase 3 will integrate an attitude control model, including a model of thruster placement on the spacecraft body. This requires the addition of an attitude control system, and an update of the formation keeping controller to manage the thrusters. The formation flight controller will be modified to correct for the delays due to attitude control maneuvering. High-fidelity thruster models will be added.

Phase 4

Phase 4 will integrate detailed models of the USU and VPI satellites, including models of their communication and control systems. The Dawgstar will integrate high-fidelity models of spacecraft hardware, with an emphasis power and communication systems. Signals will be discretized as appropriate. At the completion of Phase 4, it is expected that the simulation will demonstrate the capability to achieve mission success.

Mission Planning: Science Payload

A primary payload component of the UW Dawgstar nanosatellite design is the science instrument to conduct ionospheric measurements. As originally conceived, this payload is either a plasma frequency probe and/or a plasma impedance probe. The three university partner nanosatellites – UW, USU, VPI – would make simultaneous ionospheric measurements for a two-dimensional analysis of spatial and temporal changes in

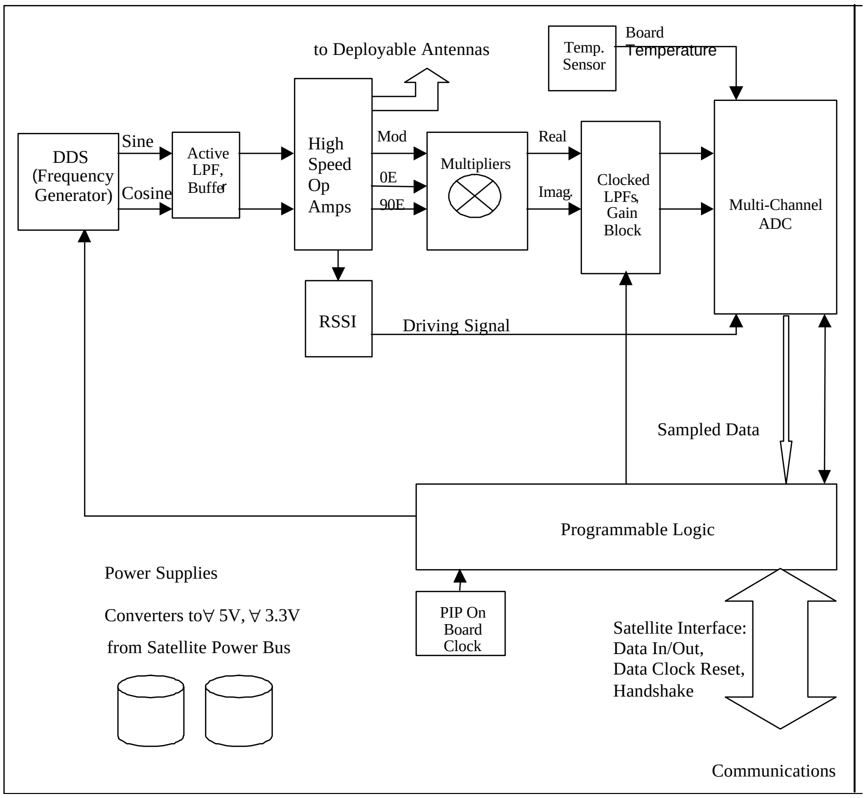

Fig. 2 Schematic of Plasma Impedance Probe

the ionospheric topography. VPI has since examined the use of the Global Positioning System (GPS) to research the ionosphere.

Ionospheric Measurements

Based on the launch vehicle's orbit insertion profiles, the UW Dawgstar's 375 km orbit will encounter random ionosphere topography. This region of the ionosphere is characterized as F2.

When conducting *in-situ* ionospheric measurements, the plasma sheath of the spacecraft is very important. If a spacecraft is at zero potential with respect to the surrounding ionospheric plasma, it collects more electron current than ion current due to the higher mobility and smaller size of the electrons. The spacecraft then gains a negative potential with respect to the plasma, which causes a region of positive charge to build up around it from which the electrons are repelled [6]. This region is described as the *plasma sheath*. The thickness of the plasma sheath varies with the potential of the electrode, but the plasma's Debye shielding length, λ_D determines the scale of thickness.

The Plasma Impedance Probe (PIP), the science instrument for the Dawgstar's mission, measures plasma outside of the plasma sheath through the use of a small deployable boom. This instrument is being designed by USU, and built by the UW. The PIP combines several technologies in order to measure the ionosphere.

The first is frequency sweeping of 0 to 15 MHz. From measuring the antenna impedance, measures of the electron-neutral species collision frequency, v_{en}, and electron temperature, T_e as well as crude measurements of electron density, n_e can be found. In addition, zero phase tracking of approximately 3 MHz can be used to measure the upper hybrid frequency of the surrounding ionospheric plasma, as indicated by the second 0-degree crossover point of the antenna (i.e., equivalent parallel resonance point). From this data, very accurate absolute values of n_e are obtained. A DC Probe can also be integrated, which is used to derive relative fluctuations of n_e. Fig. 2 shows a draft schematic of the PIP.

Structures

Dominant Structural Requirements

Environments within the payload fairing of a launch vehicle often dictate the structural requirements of satellites. The ION-F cluster will be launched from the Space Shuttle payload bay, thus the UW Dawgstar must be designed withstand the worst-case launch loads. AFRL has indicated that the fundamental vibration frequencies of each nanosatellite must exceed 50 Hz to avoid coupling with the worst-case vibration environments of the Space Shuttle [7].

The Air Force has stipulated that the mass of each demonstration nanosatellite shall not exceed 10 kg, although this requirement has recently softened. The current ejection system being considered is the Shuttle Hitchhiker Expendable Launch System (SHELS) platform, a dispenser system for small satellites and is being developed to launch out of the Space Shuttle payload bay [7]. In order to fit the ION-F nanosatellites onto the SHELS platform the Air Force has indicated that each of the three nanosatellites cannot exceed 18 inches in diameter and 10 inches in height.

General Description of Structural Design

The UW Dawgstar consists of a hexagonal prism, 10 inches high, 9 inches on each side, and 18 inches across at its largest diameter. The structure consists of two hexagonal base plates and six side trusses. The primary load-bearing structure of each hexagonal base plate is an isogrid of Aluminum 6061-T651. This material offers the best compromise between ease of machining, material cost, and material properties. The two base plates are connected in the center by a single beam passing axially through the center of the satellite. This structural support couples the drum modes of the base plates and increases the first frequencies.

Thin graphite/epoxy (Gr/E) face sheets are fastened to the exterior surface of each base plate. The exact type of composite has not been chosen, but for the sake of analysis, Gr/E T50/ERL 1962 has been used. The side trusses are also composed of aluminum 6061-T651 and are affixed with Gr/E face sheets on the exterior sides.

The primary structure has been modeled with Unigraphics and effort has been made to integrate subsystem components into the model. The aluminum frame of the entire nanosatellite is shown in Fig. 3.

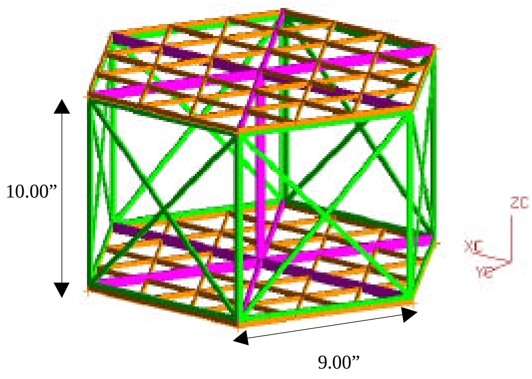

Fig. 3 Full Aluminum Frame of Satellite Bus

Propulsion

Although a wide variety of propulsion systems exist, only two types of propulsion systems are suited for the UW Dawgstar due to the mission requirements, and in particular the mass and power requirements. These two options are micro pulsed plasma thrusters and cold-gas propulsion systems. A thorough analysis of the two has been completed and is summarized [9]. The µPPT's have been chosen because of mass savings, simplicity, and the motivation of demonstrating electric propulsion for all aspects of the Dawgstar's control.

In recent years, the space industry has started to use electric propulsion to move and control spacecraft. PPT's have been used on only a few spacecraft, such as NASA's New Millennium Earth Orbiting 1 (EO-1) [8]. A miniature version of the PPT, the micro pulsed plasma thruster (µPPTs), is now in development through a partnership with Primex Aerospace Company, a leading manufacturer of electric propulsion for spacecraft, and the Washington Technology Center.

A typical pulsed plasma thruster consists of two electrodes, a solid Teflon® propellant bar, an igniter (spark plug), a feed spring, a power supply, and a capacitor, as shown in Fig. 4.

The power supply charges the capacitor, which is connected to the two electrodes. When a small plasma puff from the spark plug is released between the electrodes, the puff creates a low-resistance arc path, discharging the energy stored in the capacitor. This arc oblates a small amount of the Teflon® propellant bar and turns part of it into plasma. The current flowing through the arc also creates a magnetic field, and the resulting $J \times B$ force accelerates the plasma away from the thruster, thus generating thrust.

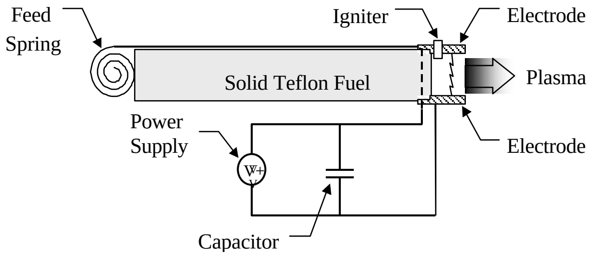

Fig. 4 Basic Diagram of a Pulsed-Plasma Thruster

The µPPT has been scaled down in terms of mass, power required, and of course thrust. The table below gives approximate numbers for the PPT and the proposed µPPT for a single thruster.

Table 1: Summary for the PPT and μ-PPT.

	PPT	μPPT
Satellite Mass (kg)	100 – 5,000	5 – 100
Impulse Bit – IBIT (μNs)	1150	800
Specific Impulse – ISP (sec)	1150	800
Energy – E (J)	50	5
Mass – m (kg)	6	1
Thrust – T (mN)	1.4	0.14

The thrusters provide enough thrust to compensate for maximum translational disturbances, due mostly to the Dawgstar's drag of 0.042 mN. The UW Dawgstar propulsion system currently consists of eight thrusters, four capacitors, eight discharge initiation (DI) circuits with igniters and one power-processing unit (PPU). There are two thruster for each capacitor. The PPU takes 28 V off the spacecraft bus and passes it through a transformer, increasing the voltage to 500 V. Next, through high voltage switching, any of the four capacitors are charged. The DI circuits are responsible for firing the thruster's spark plug, therefore identifying which thruster in that cluster shall fire.

Attitude Determination and Control

The purpose of ADCS is to stabilize the satellite and orient it in the desired direction during the mission despite the presence of external disturbance torques. Meeting this goal requires the use of sensors to determine attitude and actuators to control it. The UW Dawgstar attitude control system is tightly coupled with the propulsion system, and the choice of control method has profound effects on these systems and on mission design. Based on an overall system performance trade studies, a configuration using eight μPPTs was chosen to provide three degrees of rotational and two degrees of translational control. Micro-PPTs offer several advantages over other actuator systems, such as their low I_{bit} (70 μNs) and high I_{sp} (500 s).

The required orientation of the spacecraft (e.g., Earth pointing or inertial) and its accuracy directly influence the selection of the sensors. Other requirements such as redundancy, fault tolerance, and field of view (for Sun, Earth, or star sensors) are important in the selection of a sensor. Because of unknowns in potentially receiving donated sensors, a final selection has not been made at this point. Three sensor types have been identified, however, for use on the nanosatellite, providing three-axis attitude determination. A miniature three-axis fluxgate magnetometer made by Applied Physics Systems [9] is a viable candidate, but cannot be used when the thrusters are firing. Systron Donner [10] makes a micromachined solid-state angular rate sensor, but it's bias is questionable. Small horizon and sun sensors are also excellent choices, but they are quite expensive. The final option is to design and build simple sun and horizon sensors using small, low power CMOS cameras [11]. These would only be used to zero out the bias in the angular rate sensor accumulated throughout the orbit.

Thruster Configuration

Three-axis active attitude control systems have not, in most spacecraft, been comprised of only propulsive actuators. In the few spacecraft that do use only propulsive attitude control, twelve thrusters are typically used to provide full 6 degree of freedom control. In cases where redundancy is not necessary, fewer thrusters can be used, resulting in mass reduction in the thruster system. For a single-string failure system, it is possible to control the attitude of a satellite in all three axes with either six dedicated or four canted thrusters. In these cases, one thruster failure will result in the loss of propulsive attitude control. Both Landsat 7 and TRMM use eight thrusters for redundant attitude control [12].

Mass limitations constrain the number of μPPTs used on the UW Dawgstar to fewer than the optimal twelve. In order to achieve three-axis attitude control with reasonable control authority, and stay close to the mass requirement, eight μPPTs are used. The placement of the eight μPPTs on the nanosatellite structure is illustrated in Fig. 5.

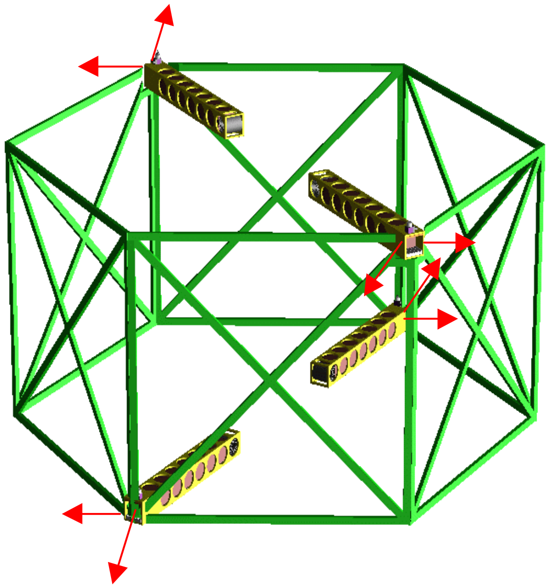

Fig. 5 Thruster Placement

This allows horizontal thrust using two thrusters, and four of the six degrees of freedom can be demonstrated using two thrusters. The propellant bars in each individual thruster are cut at angles of 45° to achieve a separation of 90° between the two thrust vectors in each thruster pair.

This configuration was chosen because it offers several advantages. First, each cluster shares one capacitor between two thrusters, resulting in subsystem mass reduction. Second, the relative thruster angles produce equal effective thrust magnitudes from each thruster, simplifying the control system of the satellite. Third, there is full redundancy in yaw and some redundancy in roll and pitch control. In the case of a thruster or thruster cluster failure, attitude can be maintained with the remaining functional thrusters.

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Although thrusters in this configuration can control the attitude of the satellite in all axes, it is limited in that it provides translational control in only two axes. The system does not have control of z-axis translation. This can be handled only by rotating the satellite and thrusting in the appropriate direction (thus the DOF is still controllable using the thrusters). Another disadvantage is that thrusters sharing a capacitor cannot be fired simultaneously. The above configuration, however, does not burden two thrusters in one cluster.

Power

The primary purpose of the electrical power system (EPS) is to generate, store, and distribute power to all subsystems during all mission phases [13]. In order to achieve this objective, a satellite power subsystem must at minimum, consist of the following three components: a power generation system, an energy storage system, and a power distribution system. Due to the nature of this project, the power generation system will be solar cells and the energy storage system will be secondary batteries. The power distribution system consists of a relatively simple design that will be constructed using modified off-the-shelf DC-DC converters.

Power Generation: Solar Cells

The current solar cell design is to place cells over all surface area not covered by other components such as antenna and deployment mechanisms. The solar cells are assumed to be high efficiency 22% or 24% solar cells from AF contractors. Preliminary calculations yield a realistic average power (after all efficiencies have been entered and all orbital elements have been simulated) of 18W. The cells must be wired in series in order to produce a voltage of 28 V, while a number of series strings are wired together in parallel to produce the proper current. In addition, bypass diodes are used with each cell in order to maintain total power output during shadowing periods.

Energy Storage: Battery

To provide a steady source of power for mission operations while in the earth's shadow, the UW Dawgstar will be equipped with a bank of secondary batteries. Acting as a power reservoir, these batteries will be recharged for approximately 56 min each orbit and must be capable of providing power during the eclipse phases of the mission. The UW Dawgstar secondary battery system will be comprised of twenty high-capacity Sanyo CADNICA KR1400AE NiCd batteries. These are connected in series to produce 24 V and are capable of providing 1400 mA-hrs of available energy per discharge cycle. The NiCd battery was chosen because of its safety record and past success as a secondary power source. The discharge curve is fairly consistent through most of its discharge cycle and it can be recharged at 0.5C to virtually full capacity within the time allowed. Although the capacity of NiCd batteries may exhibit loss due to "memory effects", or more accurately Voltage depression, the degree to which this occurs can be minimized by varying the batteries' depth of discharge (DOD) during their life cycle.

Power Distribution System

The power distribution system plays a central role in the overall design. The Series Connected Boost Converter (SCBC) configuration has been selected for the power distribution and regulation system for several reasons. The SCBC configuration eliminates the possibility of a total mission loss by providing the means for fault isolation since a power-conditioning unit is no longer required. Standard DC-DC converters have an operating efficiency of approximately 85% to 90% [16]. However, since a majority of the power is bypassed through the SCBC, the efficiency increases to 95% to 98% [10]. With the SCBC configuration, bus regulation is accomplished automatically since the PCS regulates the SCBC #2 output voltage.

SCBC technology was developed at NASA Lewis Research Center in 1993 [14]. This system is based on a standard isolated step down DC-DC converter, such as the 24 V to 12 V converter shown in Fig. 6.

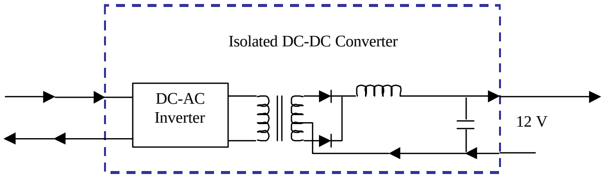

Fig. 6 Standard Isolated DC-DC Converter

A step-down DC-DC converter steps down the input voltage through the use of an internal transformer and rectifier circuitry. The primary difference between the

SCBC and a standard step-down DC-DC converter lies in the fact that a bypass connection is added to the SCBC, as shown in Fig. 7.

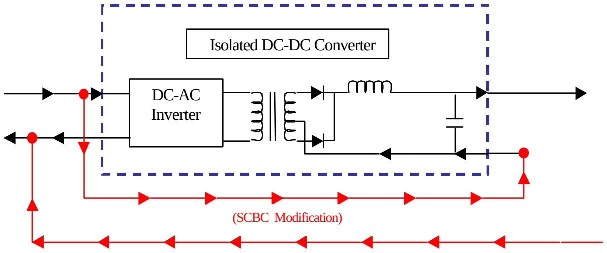

Fig. 7 SCBC Modification

The bypass connection effectively adds the converter output voltage to input voltage which in turn "boosts" the output voltage. This is shown in Fig. 8.

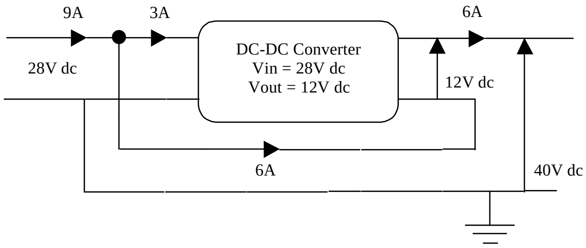

Fig. 8 SCBC Power Output Principle

SCBC #1 is used for battery charge control and consists of an off-the-shelf, isolated DC-DC converter with an interface for external control of the output voltage. This unit takes the output voltage from the solar arrays, approximately 27 V, and boosts the voltage for battery charging. As the solar array characteristics change, the Power Control System senses the SCBC output voltage and current, then varies the boost voltage of the SCBC in order to maintain a constant battery charge current.

SCBC #2 serves as the interface between the battery bus and main power bus. This unit also consists of an off-the-shelf DC-DC converter with an interface for external control of the output voltage. This unit takes the output voltage from the batteries, approximately 24 V, and boosts it to the desired bus voltage of 28 V. The purpose of this unit is to maintain the main power bus voltage at a constant level. Since the main power bus voltage is kept constant, smaller power conversion units are needed for power regulation to the subsystem loads.

Thermal

The purpose of the satellite thermal subsystem is to control and maintain spacecraft component temperatures within their specified limits throughout all mission phases [15]. In larger satellites this task is accomplished primarily through the use of active thermal control methods such as heat pipes, thermostatically controlled heaters, and louvers. Nanosatellites, however, require a passive approach due to the severe restrictions on both mass and power.

The preliminary thermal analysis of the UW Dawgstar has focused on determining the thermal environment, component temperature limits, average steady state and transient temperatures, significant thermal control issues, and thermal control hardware.

NASA Space Shuttle data indicates that payload temperatures prior to launch are from 18^o to 21^o C. During launch, the worst case temperatures that a payload experiences are predicted to be 20^o to 60^{o}C [16]. Once in orbit the thermal environment is somewhat variable depending on the orientation of the shuttle. Since the shuttle opens the payload bay doors toward the earth in order to reject heat once in orbit, the heat loads on the UW Dawgstar may be severe.

In order to model the transient condition for the preliminary analysis, the lumped capacitance method is used as described by Incropera and DeWitt [17]. Assuming a Space Station servicing mission orbit, Table 2 gives the worst case hot and worst case cold temperatures. These numbers give only an estimate of the bulk temperatures that the UW Dawgstar actually experiences once in orbit, but do assist with the initial sizing of thermal control hardware.

Table 2 Satellite Transient Temperatures

Orbit Number	WCH T_{max} (^{o}C)	WCH T_{min} (^{o}C)	WCC T_{max} (^{o}C)	WCC T_{min} (^{o}C)
One	27.1	-12.0	21.6	-15.4
Two	23.9	-13.8	17.0	-18.0
Three	23.3	-14.1	16.0	-18.6
Four	23.2	-14.2	15.8	-18.7
Five	23.1	-14.2	15.8	-18.8
Six	23.1	-14.2	15.8	-18.8
Seven	23.1	-14.2	15.8	-18.8

Two types of hardware used for thermal control have been identified: sensors and radiators. Thin film resistance temperature detectors are selected as sensors because they provide the most versatility and stability when compared to other temperature sensors. An example radiator is sized following the procedure described by McMordie [15]. In order to reject 30W of heat, the estimated radiator area is 273 cm^2 for worst case hot and 275 cm^2 for worst case cold. The temperature of the satellite is assumed to be five deg below the worst case hot temperature limit for the electronics.

Guidance and Navigation

The objective of the navigation subsystem is to determine the position and velocity vectors of the satellite as a function of time. The navigation subsystem will consist of three components: the GPS antenna, GPS receiver, and relative position software.

The GPS antenna
The GPS antenna collects range signals from GPS satellites orbiting at an altitude of 20 to 200 km at 1575.42 MHz [18]. A patch antenna located on the top of the satellite is used because it is the smallest and lightest option available. The height of only 1.4 cm will cause much less shadowing of the solar cells on top of the satellite compared to other larger types of antennas. The patch antenna in the present design is based on is the GPS antenna (RVG-201) made by Radioville [19].

GPS receiver
The GPS receiver and associated software will either be the Orion 12 receiver constructed from a Mitel GPS chipset, with Stanford orbit determination software, or an integrated cross-link/GPS receiver designing in conjunction with Johns Hopkins/APL. Although it appears at this time that the APL cross-link will be benchmarked on the ION-F satellites, only the Mitel/Stanford option is described here because the APL system has not be specified. These are both similar, however. Since Mitel does not actually sell complete GPS receivers, the Mitel Orion 12 [20] is a mock receiver design, while the Stanford design will have similar physical characteristics [21]. The current design of the GPS for the G&N system calculates updates at 1 Hz.

Relative position and velocity software
The G&N subsystem is responsible for determining the relative positions of the satellites in ION-F for use in the formation flying controls of the UW Dawgstar. To do this, software written in C must be placed in the microcontroller that is part of the C&DH system. The current Mitel receiver design only has accuracy within 100 m. Software that estimates the position and velocity of the satellites based on orbit determination has been developed by several groups including Stanford, GSFC, and APL. It is assumed that this software will enable the accuracy to achieve 10m. An additional option on the design would be to use range tone data to increase the accuracy of the measurements.

Communication System

The communication system accommodates the downlink of telemetry and the uplink of commands. Telemetry is all data transmitted to the ground including science data, satellite bus health data, and command execution verification. The intersatellite communication system, or crosslink, provides satellite GPS measurements for the formation flying mission. An illustration of these types of links is shown in Fig. 9. Fig. 10 shows the UW Dawgstar on-board communication system architecture, including the data flow through the intersatellite communication system. The tone generator sends the original tone referenced to a stable source to the crosslink transmitter and to the comparator. The tone is received by the target satellite and immediately retransmitted. The source satellite receives the returned tone and sends it to the comparator, where its phase is compared to the original tone. From the difference between these signals, range information can be calculated which could be used by the guidance and navigation subsystem. The switch shown in the figure is necessary because each satellite will act as both a source and target for range tones.

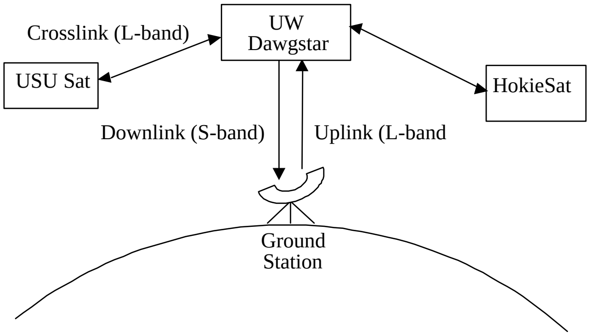

Fig. 9 Types of Links in the UW Dawgstar system.

Communication Hardware
The UW Dawgstar communication system consists of the following hardware components:

- downlink transmitter
- uplink receiver
- crosslink transmitter
- crosslink receiver
- modulator/demodulator
- antennas for Uplink, Downlink, and Crosslink
- other components (wiring, splitter, diplexer, boxes, and mounting hardware)

The L3 Communications T-400 transmitter is used for the downlink. This S-band frequency agile transmitter

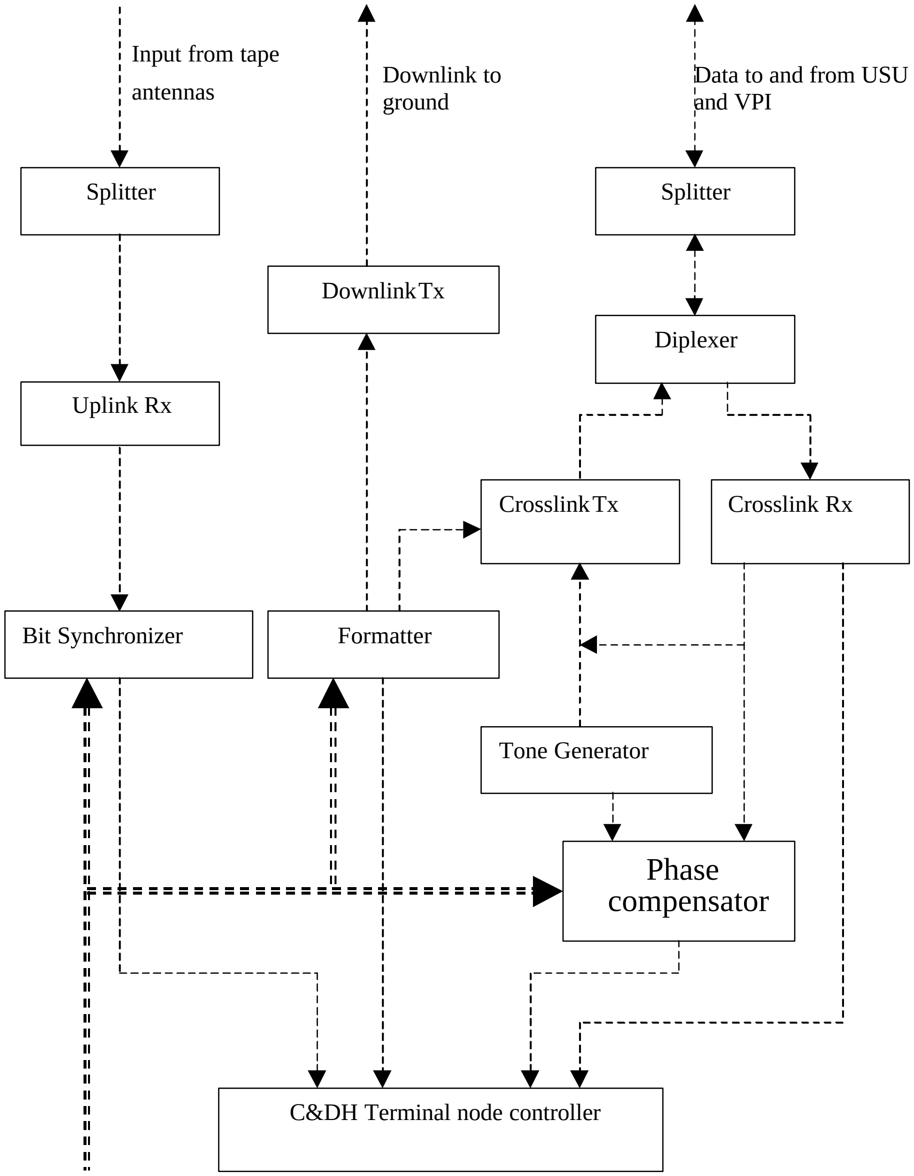

Fig. 10 Communications System Architecture

has been used for tactical video and telemetry applications. It meets IRIG standards. The off-the-shelf version of this transmitter delivers 2 W power output. It will be modified from its off-the-shelf design to deliver 1 W power output for the UW Dawgstar. The input to this transmitter is a serial cable push-to-talk and power connection. Output to the antenna is through coaxial cable.

The L3 Communications CAR-915A receiver is used for the uplink receiver. This L-band receiver has crystal frequency control. It shares the Radio Frequency (RF) section of another highly successful receiver that has seen extensive use on such missile programs as HARM, HARPOON, ITALD, SLAM (ER), and others. Input to this receiver is through coaxial cable from the antenna. Output is through a standard “D”-style connector shown in the figure.

The communication downlink uses one patch antenna. The signal is fed to the patch by a coaxial cable, with an inner diameter smaller than 0.4 cm. The only constraint is the cable must be smaller than the thickness of the antenna.

The crosslink and uplink receiver antennas are a monopole tape design. The monopole tape antenna was chosen because it can be deployed easily. It can be rolled up while the three university satellites are connected together. Once the satellites separate, the tape antenna will roll out into its natural position due to its restoring force. The tape antenna is 19 cm in length, and all five weigh approximately 0.15 kg, including the mounts. The simple mount will be used for the tape antennas on the edge and bottom of the satellite.

The characteristics of the intersatellite communication system will be determined by the Applied Physics Laboratory (APL) crosslink hardware proposed for the ION-F flight. Hardware is being developed by APL and will be made available to the ION-F team through a grant by NASA Goddard Space Flight Center (GSFC).

Command Strategy

The command strategy chosen for the UW Dawgstar is the repeat and execute (R&E). The R&E strategy has the least potential of producing errors when communicating with the satellite. Since the satellites in ION-F are communicating with a ground station only two to three times daily, it is possible that the amount of commands that need to be transmitted during an access time are high. In that case, there is little time to wait for verification transmission from the satellite before the ground station sends an "execute" command.

For the (R&E) strategy each command is transmitted to the satellite twice with no time gap between transmissions. Both transmissions are received and processed and if they are identical, the command is executed. Once the command is executed, it is echoed to the ground station within the downlink telemetry to verify that the proper command is executed. If both transmissions do not match, the satellite reports the error to the ground station in the downlink telemetry. The ground station retransmits the proper command using the same strategy. The advantage to using this strategy is that it is simple and inexpensive. It is useful in situations where real-time feedback is not practical.

Ground Station

There will be two ground stations, one at USU and one at VPI. The satellites will uplink and downlink at the same frequencies, and thus must share the access time. The frequency bands have been applied for through AFRL. The UW will send commands to the ground stations through an internet connection which will then be transmitted to the satellites. In this way the UW will be able to communicate with the UW Dawgstar without having a ground station at the UW

Command and Data Handling

The Command and Data Handling (C&DH) system is a combination of software and hardware that manages the subsystems of the UW Dawgstar satellite. Specifically, the C&DH subsystem uses a high speed data bus to facilitate transfer of data between subsystems, prepares telemetry for downlink, distributes telemetry from uplink, and performs system maintenance and checks.

Fig. 11 shows the system architecture diagram for the Command and Data Handling System. Each device is connected to the flight computer, which acts as the central node of the system. Any component failure, other than the main computer, will not affect the functionality of the system as a whole.

The CPU is the center for all of the spacecraft's operations, as it can receives and processes data as necessary, stores data in bulk memory, or passes data on to other subsystems, such as communications. The Tattletale 8 (TT8) data logger/controller from Onset Computer has been chosen. The TT8 consists of a Motorola 68332 microcontroller as the main processor and has fast sampling rates, extensive control functions, and sophisticated computational ability [22]. For the boot program storage, the TT8 has on board Programmable Read Only Memory (PROM). PROM is a type of memory that can only be read from, and usually holds the programming that allows the computer to be booted.

For the Dawgstar, either Erasable Programmable Read Only Memory (EPROM) or Electronically Erasable Programmable Read Only Memory (EEPROM) could be used. EEPROM was chosen over EPROM because the latter can be written to more than once by exposing the chip to ultra-violet light for a short period of time – not an acceptable choice because the spacecraft will be subjected to bright sunlight during its lifetime. EEPROM requires an applied voltage to erase. The TT8 contains 256 KB of EEPROM to store its boot program.

The bulk memory stores spacecraft subsystem programs and data to be processed by the CPU, or to be downlinked or crosslinked. The data are stored into Random Access Memory (RAM). For the UW Dawgstar, 32 MB of Ram will be used. The Input/Output (I/O) board is the connection between the CPU and any device that either inputs digital data to or outputs digital data. These devices include sensors, actuators, the science experiment, and the communications system. The I/O board is available from Onset Computers Corporation.

The Terminal Node Controller (TNC) is the primary interface between the Communications and the Command and Data Handling subsystems. Digital data to be downlinked or crosslinked is transmitted from the flight computer in a binary serial stream form to the TNC. The TNC packetizes the data into a protocol format, X.25 in this case. The TNC then modulates the

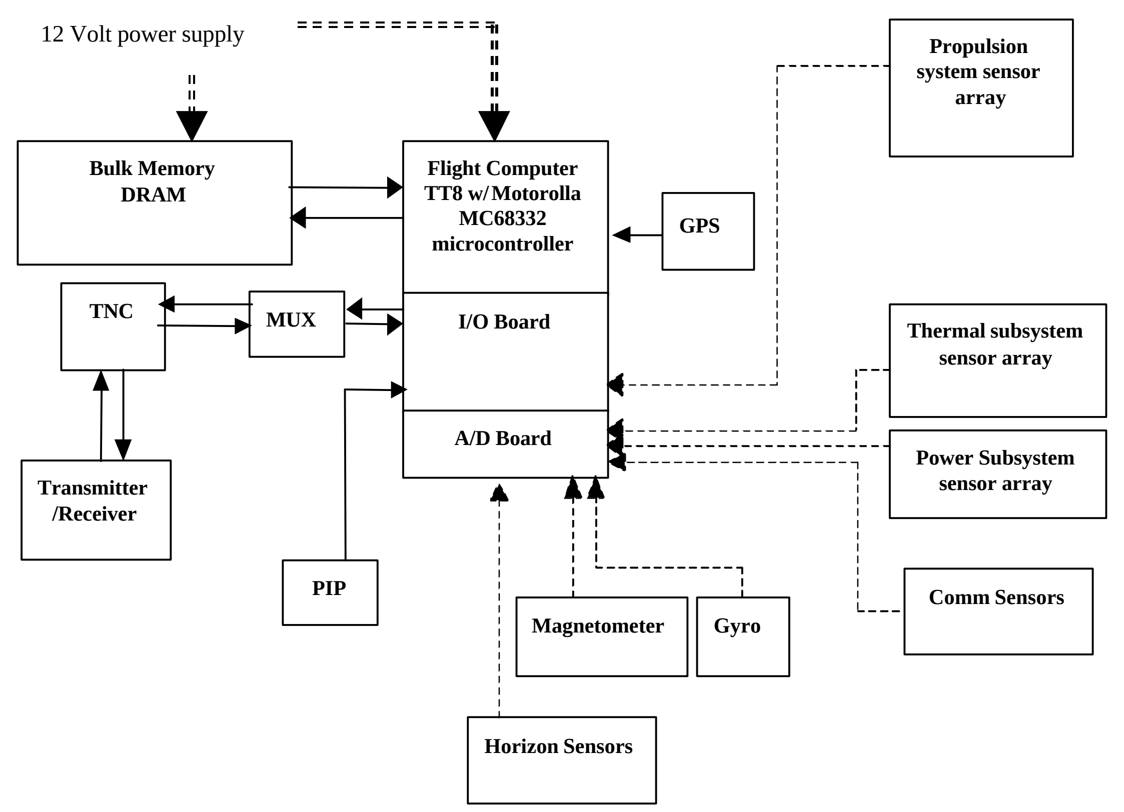

Fig. 11 Command and Data Handling System Architecture

data using frequency shift keying (FSK), and the data packets are sent to the transmitter and placed on a carrier wave for transmission. When data is coming into the spacecraft from the ground or from other satellites, the process is the same only in reverse order.
The multiplexer is a board that interfaces between the flight computer and the TNC. This board allows multiple devices to input data into the TNC pseudo-simultaneously. The multiplexer takes individual data streams coming from different devices and samples each stream at different time intervals. The data are then combined into a single stream and input to the TNC to be formatted for transmission. The multiplexer is a small board that will most likely be attached to the TNC and mounted in the same enclosure.

The system bus is the path that the data travels when going from one component to another, i.e. the wiring. Digital data can be transferred by serial or parallel. Serial indicates one event at a time, where time separates the transmission of individual bits of information. Space division is used for multiple bits sent in parallel, either through multiple lines or multiple paths [23]. Data transfer using serial communication is slower than parallel communication; however, serial communication is sufficient for the Dawgstar. The UART is a chip located on each serial device and controls the transmission of data across the serial bus. The UART adds a parity bit to outgoing transmissions to determine if the data is received from its source. The bit is discarded after it is received and does not add to the size of the data. The UARTs also follow the RS-232C standard that describes the physical interface and protocols between serial components in the spacecraft. The software that will run the satellite is written in the C programming language. Onset provides a C-compiler, debugger, developers kit, and manuals.

Data Rate Budget

The data rate budget (DRB) is constructed in order to aid in sizing the C&DH subsystem. The data rate budget sizes all of the sources of data in the satellite, such as the temperatures on a solar panel or position data from the GPS unit. The DRB contains the quantity, sampling rate, and word size. This information is used to find the data rate required for each device, the overall satellite data rate, and memory required for downlink. Current estimates show approximately 0.98 Kbps of data being communicated through the satellite. This is limited by the amount of ground station access time.

Conclusion

The preliminary design of the UW Dawgstar has been shown in as much detail as possible. Wherever possible, the actual hardware components chosen have been specified and references given. The design for all the subsystems is adapting continuously as testing is conducted and the design matures.

Acknowledgements

The authors would like to acknowledge Primex Aerospace Company for their design insights and propulsion collaboration, and the students of the AA 420/421 Space Design Course for their hard work and dedication to the program. This work was supported under contract Grant Number F49620-99-1-0230 from the Air Force Office of Scientific Research.

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