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TSAT Solid State Detector and Plasma Probe Particle Detectors

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Abstract

Along with its other sensors, the Taylor Satellite (TSAT) houses solid state detectors and a plasma probe to take in-situ measurements of space weather. Both the solid state detectors and the plasma probe provide location specific data throughout the orbital lifetime of the satellite. As an outgrowth of the Engineering Senior Capstone class, student work for the solid state detector includes prototyping the front end circuit and setting up 16 processor counters to track the number of particles detected. Major features of the plasma probe involve its adaptation to use 5V power instead of 9V and matched transistors in an amplifier feedback loop to create a logarithmic scale. Both the solid state detectors and the plasma probe share a PIC18F2620 microcontroller. The microcontroller collects count data, controls the voltage sweep, reads temperatures at the transistor junction, and communicates serially with the instrument processor board. Developing the solid state detectors and plasma probe systems serves the dual purpose of furthering satellite research and education. Working with a diverse team on a project with real costs, deadlines, requirements, and an actual launch with NASA, is an invaluable Engineering Senior Capstone learning experience for the students involved. Also, having the opportunity to work with specialized instrumentation like the particle detectors offers students a unique exposure into the challenges facing circuit and processor algorithm designs.

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Introduction

The Extremely Low Earth Orbital (ELEO) region of space presents a vast opportunity for discovery and scientific research. Taylor University's cube satellite, TSAT, will be released for orbit at 325 km and will travel around the earth for nearly 5 weeks before combusting in the earth's ozone at an altitude of about 80 km. TSAT will be equipped with particle detectors, UV radiation sensors[3], and Electric field and very low frequency (VLF) detectors[7]. The satellite data retrieved has the potential to provide invaluable insights into the current state of knowledge on space weather patterns in the relatively uncharted ELEO region. To manage this data, an on-flight processor and ground support equipment (GSE) station have been designed[4]. To continue the legacy of space exploration at Taylor University, the future work of the ELEO satellite (ELEO-Sat) project will benefit from the present TSAT research project and mission[8]. Both satellites will contribute to a better understanding of the ELEO region by enabling predictions of orbital decay, while testing the performance of current low orbital communication networks. TSAT is expected to be launched from Cape Canaveral in the summer of 2013 and followed by the launch of ELEO a year later in 2014. Both of these projects establish platforms for student creativity, discovery, and the furtherance of educational targets through project based learning activities.

Overview

Along with its other sensors, TSAT will house solid state detectors and a plasma probe. Among these instruments are included: particle detectors that take in-situ measurements as well as solid state detectors and a plasma probe for measuring particles in the vicinity of the craft itself. This makes cubesats an invaluable tool for understanding and tracking the regions of space that are currently not well understood.

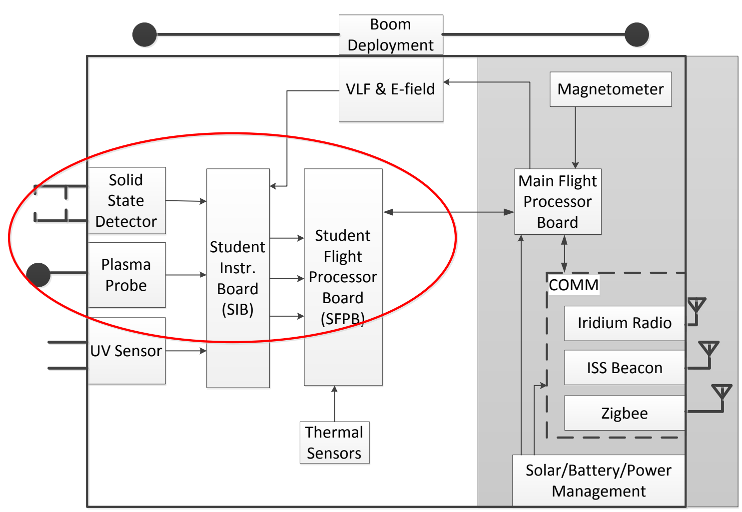

Figure 1: TSAT High Level System Diagram

The collision of high energy particles with the solid state detectors renders a pulse, the height of which can be related to the energy of the incoming particles. The magnetic field lines of the Earth have a significant influence on the paths of these high energy particles. Specific view angles are there required to capture the particles travelling along these paths.

The plasma probe is another instrument aboard TSAT that measures electron temperature and density in plasma. Plasma is a region of space consisting of free electrons and positive ions. To get information about concentrations of these particles and their temperatures, an electrode is inserted into the plasma region at a known voltage. This electrode then attracts ions or electrons—depending on its charge—and a current is induced in the circuitry. Sweeping the electrode voltage and reading currents create a current versus voltage (I-V) characteristic plot from which electron temperatures and concentrations can be calculated.

TSAT has many interdependent subsystems. For the solid state detectors, there are eight processors per detector that record the number of counts in each energy range. These counters, along with the plasma probe, are dependent upon the solid state detector/plasma (SSDP) processor for polling data. (The SSDP processor depends upon the student flight sensor processor[4] for polling data.) Next, a flight communication processor polls data from the student flight sensor processor to send the data over the iridium network to a ground support station. These interdependent processes of sensing, processing, sending, receiving, and analyzing data require a high level of testing and system integration. To aid in this process, the drafting of formalized interface documentation has been crucial, as have low and high level diagrams (Figure 1 and 2), and regular project team meetings.

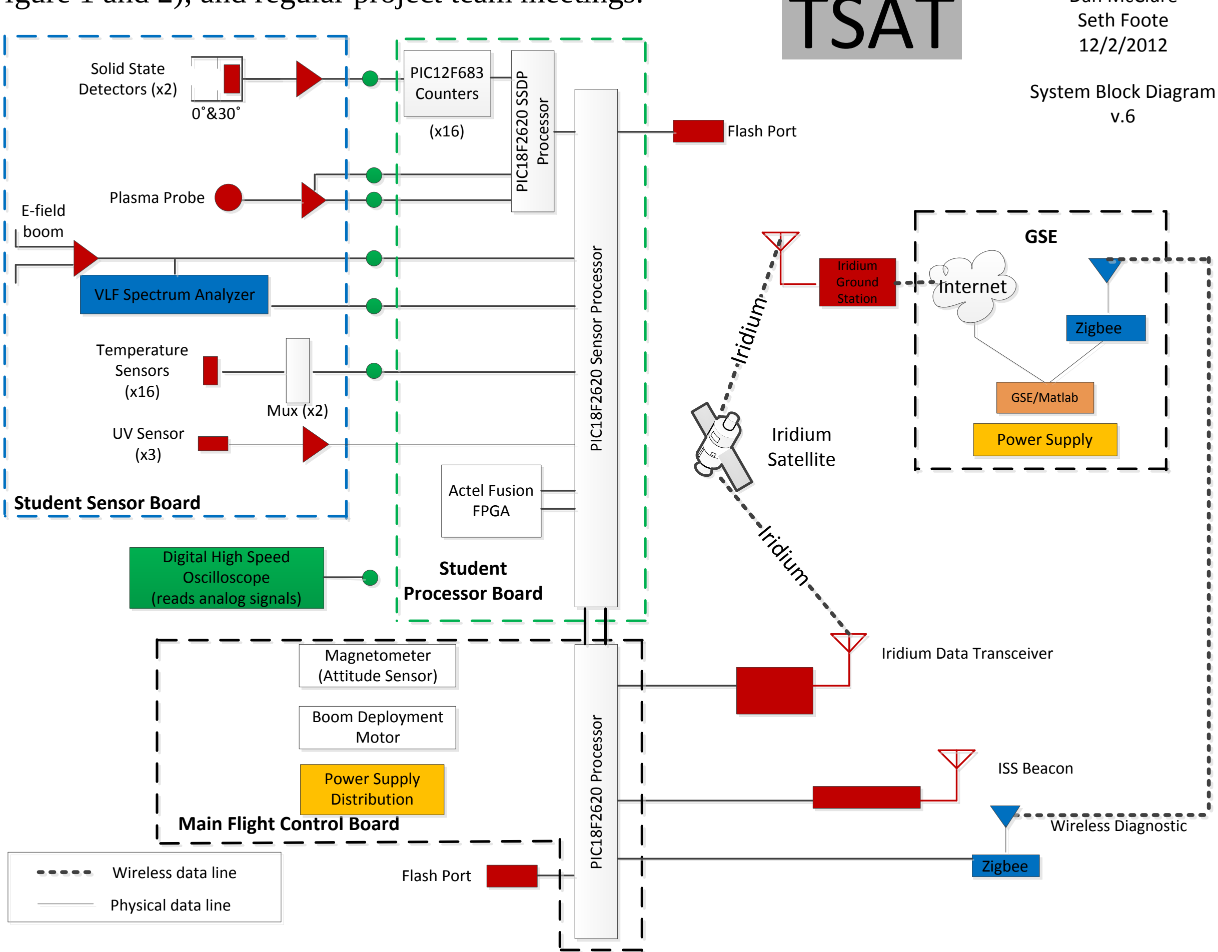

Figure 2: TSAT Low Level System Diagram

Sensors

Description

The solid state detectors are housed in a section of TSAT dubbed the Capstone Sensor Bay as situated towards the rear end plate of the satellite, and face outwards through a hole in the side plating to enable unhindered viewing of the astronomical horizon at an inclined angle of 30°. From the sensors themselves, coaxial cables run to the student sensor board with the circuitry to process and count the pulses. A PIC18F2620 processor then polls 8 channels of counters per detector and communicates this data to the rest of the craft. The same processor controls the plasma probe circuitry which is also housed on the student sensor board. A coaxial cable runs from the plasma probe circuit to the electrode situated on the forward end plate. This location is ideal for collecting in-situ plasma data as it puts the sensor at the very leading edge of the satellite during its orbital flight, i.e. prior to the plasma matter making contact over the remaining surface of the craft as it hurtles through space. The electrode in this instance consists of a gold plated antenna. (For more details about interfacing, refer to Lew et al.[4]; as for details about the mechanical components, refer to Seifert et al.[7])

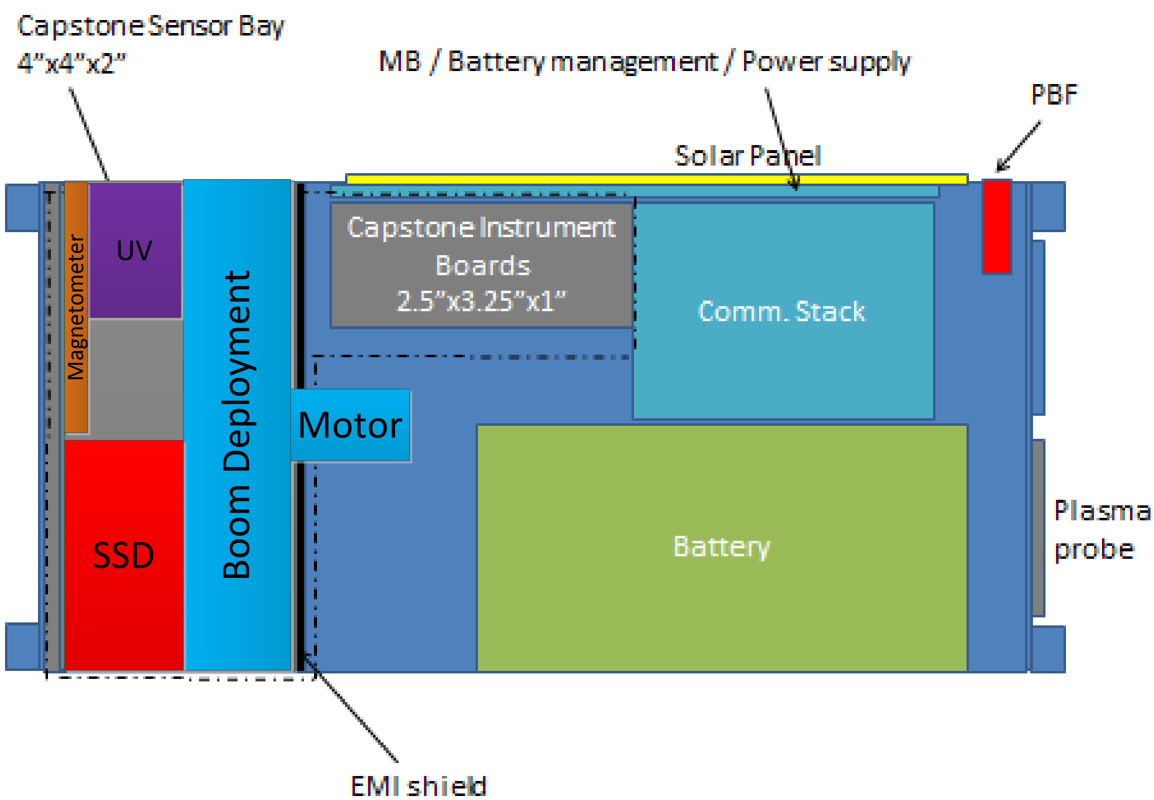

Figure 3: TSAT Bays and Space Allocation Diagram

The designs of both the solid state detectors and the plasma probe involved work prior to the Engineering Senior Capstone class. The former solid state detector project included prototyping the front end circuit, developing the particle counting circuitry and processing, and the building of telescopes for housing the detectors. Currently, the counting is accomplished via 16 individual processor counters. The plasma probe includes modifying the circuit to use new amplifiers and, as such, eliminates the circuitry that otherwise would have been required to create the plus or minus 9 volts for operational amplifier power rails. Because these two sensors use the same processor, both the solid state detector and the plasma probe data algorithms are joined together.

Solid State Detector

A solid state detector (SSD) is very similar to a Geiger counter in its functional purpose. Rather than using a sealed gas and high voltage probe, a SSD uses a silicon depletion region to absorb a particle's energy and transfer it to a charge. When an electron enters within the field of view (FOV), it passes into the silicon region of the detector. Particle detectors like this use an electrode plate to collect a building up of voltage or current. Due to the unique electron pair properties in silicon, a charge to energy relationship can be made. This relationship can be calculated by the follow equations:

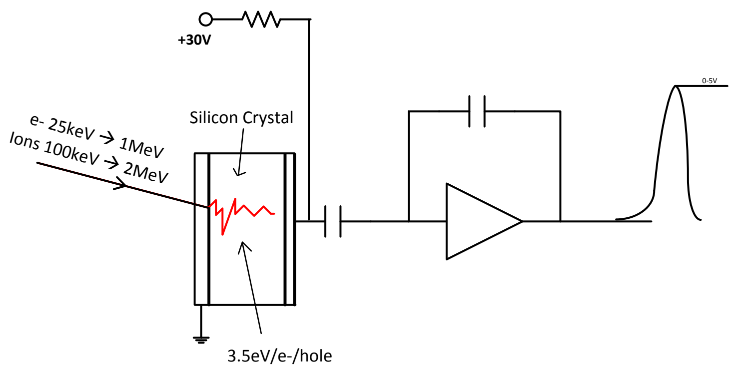

Figure 4: Solid State Detector Physics

$$Q = \frac{Particle\ Energy}{3.5eV/e^-} * 1.6 \times 10^{-19} \qquad (1)$$

Where 3.5 electron volts per electron hole pair is a property of silicon.

For example, an electron with 500,000 electron volts of energy would produce a 22.8 femtocoulomb charge on the electrode plate as shown by the following calculation:

$$\frac{500{,}000eV}{3.5eV/e^-} = 143{,}000e^- = 22.8fC \qquad (2)$$

. Table 1 lists the relationship for low, typical, and high energy levels of incoming particles.

Table 1: Expected Charge Range

Particle Energy	Charge
25keV (Low)	1.14 fC
500keV (Typical)	22.8 fC
1MeV (High)	45.7 fC

The SSDs use a high quality, light-tight sensor that outputs a step signal which is proportional to the energy of the detected particle. This feeds into a front end circuit that shapes the step signal into a smooth pulse that can be counted with a timer on a processor chip. The concept for the front end circuit was originally developed by a prior student at Taylor University[5], which enabled for a quick design to be implemented for the present TSAT project.

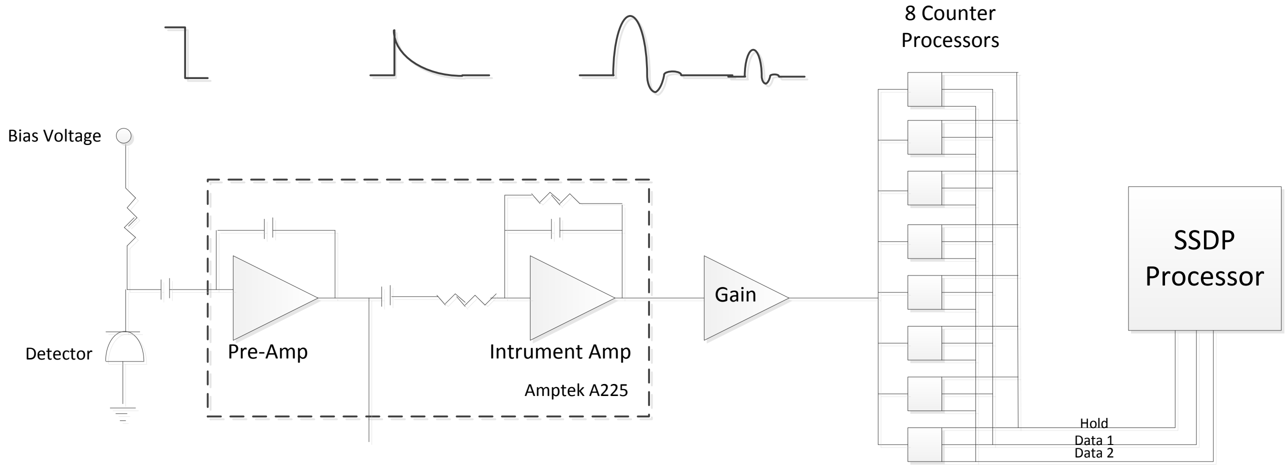

Figure 5: SSD Block Diagram

The Amptek A225F is a unique, flight certified filter, specifically used for SSDs. The A225F consists of a pre- and shaping-amplifier followed by an instrument- and shaping-amplifier. The output of this device provides a timing pulse and a smooth shaping pulse as shown in Figure 5. (Refer to Figure 6 for the Amptek A225F block diagram with symbolic labels .) The transfer function of this device can be shown as follows:

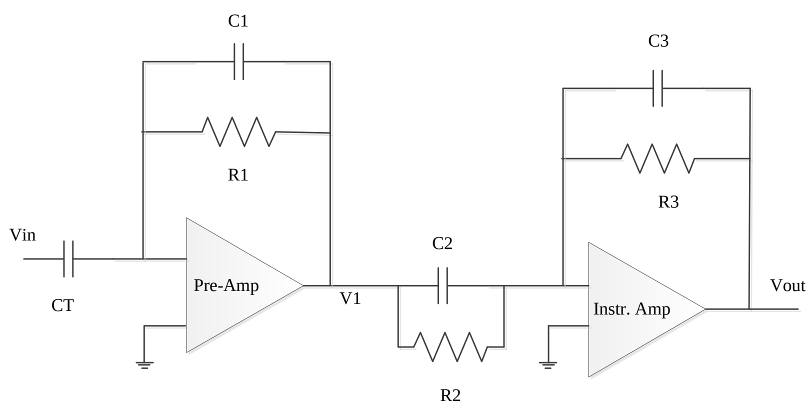

Figure 6: Amptek A225F Mathematical Modeling

$$\frac{V_{out}}{V_1} = -\frac{j\omega C_2 + \frac{1}{R_2}}{j\omega C_3 + \frac{1}{R_3}} \tag{3}$$

$$\frac{V_1}{V_{in}} = -\frac{R_1}{j\omega C_T + j^2\omega^2 C_1 C_T R_1} \tag{4}$$

By multiplying equations (3) and (4) together, the A225F transfer function is found to be:

$$\frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_1} * \frac{V_1}{V_{in}} = \frac{j\omega C_2 + \frac{1}{R_2}}{j\omega C_T (j\omega C_1 + \frac{1}{R_1})(j\omega C_3 + \frac{1}{R_3})} \tag{5}$$

TSAT will have a pair of SSDs each of which will be oriented at different angles. Since high energy electrons follow the magnetic field lines, the highest counts of electrons will be measured where the sensor is perpendicular to the magnetic field lines. However, the magnetic field lines do not always intersect at right angles to the sensor as the field lines are not perfectly circular. Therefore, covering two view angles with non-overlapping FOVs allows for a Poisson distribution to be reconstructed. Since TSAT will be flying below the radiation belts, lead shielding will prevent particles from entering that are not within the FOV. The FOV will be formed by using 2 collimators to deflect or absorb unwanted particles. The collimator ring diameter is based on the distance from the SSD sensor lens to form a perfect 20˚ FOV.

By using a 3D printer, both the manufacturing approach and the end-product features were enhanced from what could formerly be achieved by using the more conventional manual machining methodology. Since a 3D printer can easily build internal cavities, the final design shows modifications to simplify assembly. Additionally, a 1.6 mm (1/16 inch) tolerance was designed to allow for the placement of lead shielding tape in between the outer and inner parts. The design has two collimators, an insulated spot for the sensor, a coaxial cable hole, and screw holes for mounting.

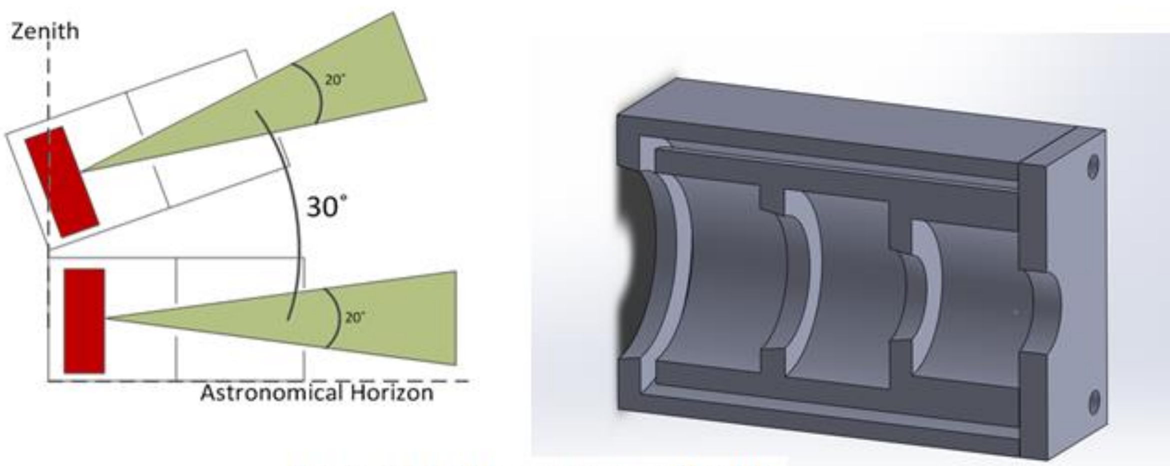

Figure 7: SSD Mount Angles and FOVs

Plasma Probe

The plasma probe is an important tool for space weather modeling. With other instruments such as electric field detectors, SSDs, and magnetometers, the probe offers researchers valuable data in the ELEO regions. If satellites flying plasma probes became sufficiently cheap, constellations could be flown to further map the ionosphere[1]. The data taken will also be useful for further studying the coupling of atmospheric layers[2]. While plasma probe readings have been ongoing for some time, flying a probe on a satellite brings in much more meaningful data than that obtainable by rocket flights which ascend and descend through the expanse of space of interest in too rapid a fashion.

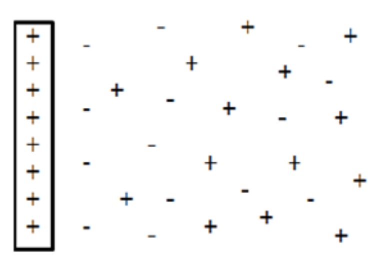

Figure 8: Electrode in Plasma

At its heart, the plasma probe, or Langmuir probe, simply consists of a metal rod placed in a region of plasma *Figure 7: SSD Mount Angles and FOVs* that then draws current. In more technical terms, it is an electrode at a known voltage being held in the plasma domain. Either the thermal electrons or the ions contained in the plasma get attracted to the electrode because of its potential; also, due to the moving charges, a current is consequently induced in the electrode. At the various voltages that are being applied to the electrode, the corresponding currents can then be recorded. With such information, a current versus voltage plot can be constructed to ascertain the density and temperature characteristics of the electrons and ions in the plasma[6] (see Equations (6) and (7)). The plasma probe flying on TSAT uses only positive voltages, and so it is limited to furnishing data about the plasma electrons alone. That limitation, however, does not prevent accurate modeling of ion properties after the electron temperature and concentration are known.

$$i = i_0 \exp(-\frac{eV}{kT}) \qquad (6)$$

Where i is current, e is the electron charge, V is voltage, k is Boltzman's constant, and T is the electron temperature.

$$\frac{i_0}{A} = \frac{1}{4} nev_e \qquad (7)$$

Where i again is current, n is the electron concentration, e is the electron charge, and v is the electron velocity.

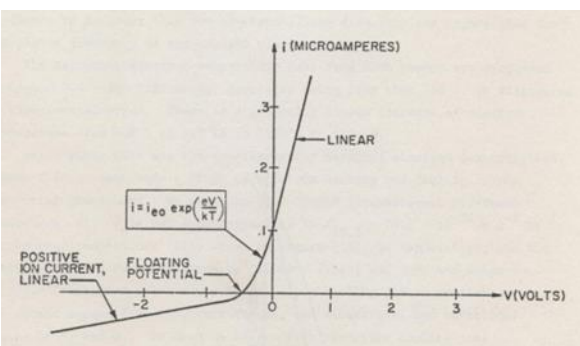

Figure 9: Plasma I-V Curve[6]

On a logarithmic I-V plot, the electron temperature is inversely proportional to the slope of the ascending branch of the curve and the electron density is proportional to the current that is being measured[10].

The supporting circuitry for the plasma probe located on the student sensor board fulfills two primary purposes: (i) providing the required electrode voltages, and (ii) reading the resulting currents. To generate an I-V curve, the electrode voltage is swept from 0 to 4 V, as accomplished with the pulse width modulator of the PIC18F2620 processor. Most of the circuit is designed for reading the currents induced by the electrode voltages. Current flows from the electrode and through the coaxial cable to the circuitry on the student sensor board, where it is run through a logarithmic electrometer which serves as an opamp by inverting the configuration with a pair of matched transistors in the feedback loop. These transistors act as a pair of diodes and create the logarithmic scale. After passing through the electrometer, the signal passes through an instrument amplifier and goes to the processor. Previous designs included front end circuitry to generate ±9V for the operational amplifiers, but the use of a new amplifier only requires ±5V rails making that part of the sensor obsolete. Unfortunately, the logarithmic electrometer is sensitive to temperature changes which can add unwanted factors to the current data that is being received. To circumvent this, a circuit with a temperature transducer tracks the temperature at the electrometer's transistor junction, resulting in current readings to be interpreted with respect to that particular temperature.

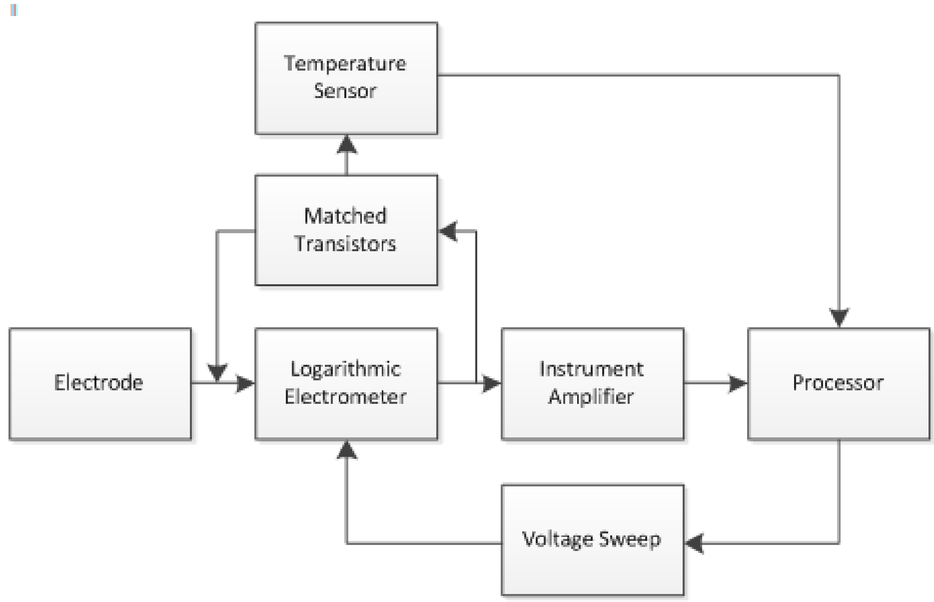

Figure 10: Plasma Probe Block Diagram¶

Digital
Data

For better interpretation, the plasma and SSD data should be displayed on graphs with position as the independent variable. Graphs show how the readings can fluctuate all the way between the South and North Poles. SSD data is best displayed in counts per second and plasma data is best displayed as current versus position. A Poisson distribution for the count rate versus energy at a specific area in space is also useful.

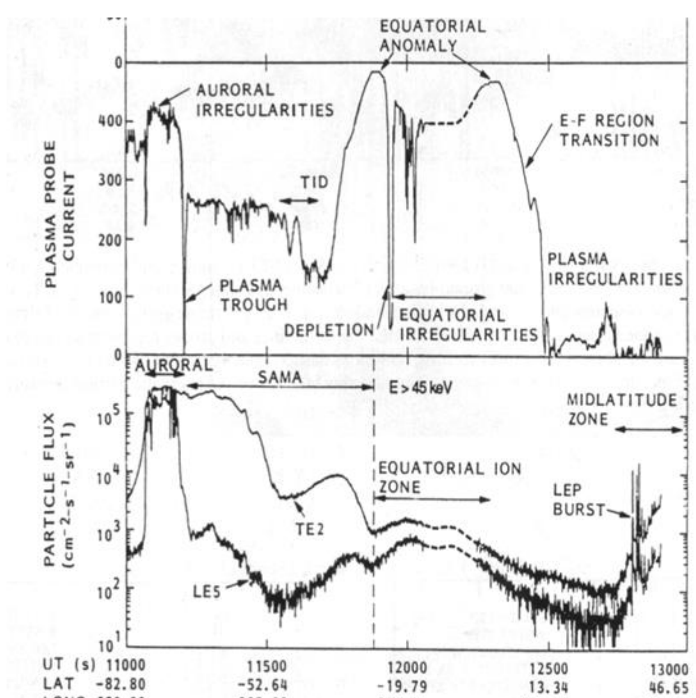

Figure 11: Expected Data[9]

Processors on SSD

To meet the requirements for eight channels of resolution, a change was made to prior hardware design. Eight individual processors were used per detector for each set with different reference voltages. This allowed for counts to be recorded from eight different energy ranges. Every second, a dual purpose processor polls data from the eight solid state detector processors and saves the number of counts in the memory. Figure 5 shows the block diagram layout of the detector, amplifier circuit, eight processors, and the dual purpose processor called the SSDP.

Each counter processor has three connected data lines: RX, TX, and HOLD. The RX and TX are serial receive and transmit lines. The HOLD line acts as a trigger and tells all the counters to shift the current count values into a variable. Immediately following, the processors return to counting particles while listening for their individual addresses to be called. When an address is called by the SSDP processor, the corresponding counter processor sends the variable with the count data over its TX line. When all 16 of the processors are serviced by this loop, the HOLD trigger is released and the 16 counter processors go back to waiting for another data poll from the SSDP. Based on this algorithm, each counter gets assigned a unique address.

SSDP Processor

The SSDP processor communicates with the student flight processor via serial, asynchronous communication. As stated earlier, the SSDP processor serves to collect data from both the SSD and the plasma probe. A function byte is received by the SSDP processor each time the student flight processor polls data. This function byte first specifies when the data is being captured in low or high speed modes. Since TSAT begins to deorbit more rapidly during the end of its mission, a high speed data collection mode is used to capture the most data possible. The function byte also specifies if the data requested is normal data, calibration data, or plasma sweep data. Since the flight processor operates at a single poll/second, the normal data request does not have sufficient time to capture the plasma probe data sweep. This is because a plasma sweep takes longer than a second to ramp to the pulse width modulator wave used to create the I-V curve. Therefore, this function is only called on command every five minutes in low speed mode and each minute when operating at high speed. After the SSDP processor receives the function byte, it captures and sends the requested data.

During normal polling, the plasma probe electrode is held at 4 V. When the SSDP processor runs a plasma sweep or a calibration, however, the electrode voltage sweeps from 0 to 4 V in .5 V increments. In a voltage sweep, the processor takes eight readings from the plasma probe, one at each voltage step. A reading consists of current and temperature data. Calibrations use the same sweep and the same eight readings. Moreover, during a sweep, the SSDP processor verifies that the voltage sweep is running correctly by reading in that voltage. This last bit of information, however, is not sent to the student flight processor, unlike that of the current and temperature data. The typical high resolution sweep was decreased to reduce the data and sensor polling times. This lower resolution sweep takes half the volt steps needed per reading at each level.

Capstone learning objectives

The TSAT project has provided students with many essential learning experiences. Some of the more noteworthy ones are:

1. A challenging new system level project
2. An avenue for creativity
3. Implementing the ABET design process through an actual project
4. Learning cutting edge software skills, e.g. SolidWorks, Orcad, Simulink, and Visio

Additionally, the multidisciplinary nature of the team also provided students with invaluable lessons for working together in diverse groups to realize the larger scope of the project while requiring accountability of each individual regarding their own subsystem's design. The critical design review (CDR) held before the engineers at ITT Exelis also helped refine the design plans, the team's professional presentation skills, and packed real world project expectations into the otherwise academic learning environment. Lab work, equipment familiarity, and system integration have all been integral to the overall learning objectives of this significant student design venture.

Conclusions

While the plasma probe and solid state detector make up only two of the many varied instruments aboard the TSAT project as was discussed in this paper, these nevertheless account for a large amount of the space weather data that is appropriated. The plasma probe contributes to a fundamental understanding of charged gas particles in relation to concerns such as radio communications and atmospheric layer coupling. The information collected by the solid state detectors is used to advance the state of knowledge of the ionosphere, a region of the atmosphere that is not that well understood at present.

Academically speaking, the project has proven to be an effective means of bridging the classroom learning objectives together with real world hands on circuit design and software programming and implementation, and the achieving of actual project milestones. .

Acknowledgements

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