Design and Development of HAUSAT-1 Picosatellite System (CubeSat)

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Abstract — This paper addresses the development and design of the HAUSAT-1 (Hankuk Aviation University SATellite-1), a new generation picosatellite, being developed by SSRL (Space System Research Lab.) of Hankuk Aviation University. This project is funded by Korean Government for the purpose of developing the space core technology. This is the first satellite development program executed at the level of university in Korea. The CubeSat project is to develop the satellite weighing less than 1 kg and provides opportunities with low construction, low launch cost space experiment platforms with shorter production cycles.

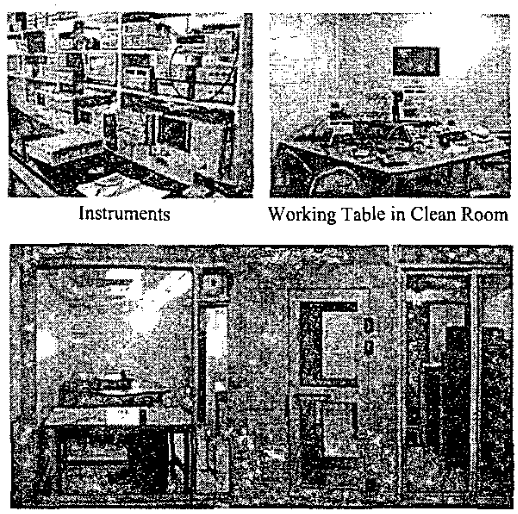
The HAUSAT-1 project offers graduate and undergraduate students great opportunities to be able to understand the design process of satellite development and have practical experience as a team member. Its mission objectives are collecting the satellite position data with spaceborne GPS receiver, experiment on deployment mechanism of solar cell panel and homemade sun sensor, and getting data related to satellite SOH(State of Health) data from various sensors. The HAUSAT-1 will orbit at the altitude of perigee 600 km ~ apogee 650(~900) km with 98 degree inclination angle as sun synchronous for 1 year of design mission life. The HAUSAT-1 is planned to launch in the third quarter of 2004 by the Russian "Dnepr" launch vehicle.

INTRODUCTIONS

In recent years, the trend of the satellite development is toward "smaller, faster, cheaper, better".[1] Many countries are focusing on developing small satellites such as microsatellite, nanosatellite, and picosatellite for the development of space technology with shorter production cycles. Currently various universities in the world are developing nanosatellite and picosatellite for the purpose of educating satellite design discipline and verifying space technology in space environment. Small satellites tend to use COTS(Commercial-Off-The Shelf) parts and standardized platforms and are built on a cheap and simple assembly line. The HAUSAT-1 is a new generation picosatellite weighing less than 1kg with 10 cm x 10 cm x 10 cm cubic configuration.[2]

The HAUSAT-1, a CubeSat which is being developed by Space System Research Laboratory (SSRL), is low cost satellite for education and space technology demonstration. SSRL is one of the National Research Laboratory (NRL) supported by Ministry of Science and Technology (MOST) in Korea to contribute space core technology development. SSRL is the first university small satellite system development lab. in Korea and staffed by full-time students of Ph.D., M.S. & B.S. courses and fully equipped with satellite diagnostic hardware and the latest computer simulation systems and tools. As shown in Fig. 1, the major AIT equipment and facilities are consisted of various electronic equipment, spacecraft simulator and class 100,000 clean room.

This paper addresses detail design and trade-off results of HAUSAT-1 satellite.



Instruments | Working Table in Clean Room

Class 100,000 Clean Room

Fig. 1 Space System Research Lab. Facilities

MISSION ANALYSIS

The primary mission objective of HAUSAT-1 satellite is to offer graduate and undergraduate students great opportunities and help them understand the whole development process of satellite design, analysis, manufacturing, assembly, integration, test, launch and operation, and consequently make them specialists in the field of satellite development. Actual mission objectives

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in accordance with on-board payload are as followings; collecting the satellite position data with spaceborne GPS receiver, experiment on deployment mechanism of solar cell panel and homemade sun sensor, and getting data related to satellite SOH data from various sensors, whose data will be used to design the HAUSAT-2 nanosatellite in the future. The design mission life of the HAUSAT-1 satellite is expected to be 1 year.

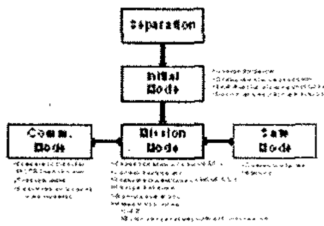


Fig. 2 Operation Mode

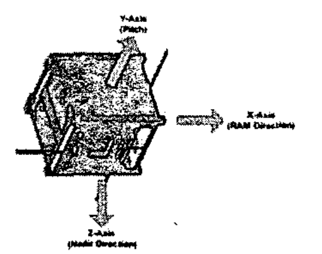


Fig. 3 Coordinate System

Table I Power Budget [mW]

	Int.	Mission	Comm.		Safe
			CW	Tx	
Payload	0	500	0	0	0
ADCS	0	0	0	0	0
EPS	50	50	50	50	50
OBC	60	60	60	60	60
CS	850	170	190	370	120
TCS	200	200	200	200	250
SMS	0	0	0	0	0
Margin	80	70	100	70	70
Total	1250	1050	600	750	550

Table II Total Mass Budget

	Mass(g)
Payload	160
ADCS	60
EPS	210
OBC	45
Communication	140
TCS	30
Structure	270
System Margin	85
Total	1,000

The HAUSAT-1 has four types of operation modes as shown in Fig. 2; Initial Mode, Communication Mode, Mission Mode, and Safe Mode. The power requirement at individual mode is different and calculated by considering average and maximum power consumption. In the case of initial mode, the system power is supplied only by battery before the solar cell starts to generate power. Therefore, it is required to charge the battery fully prior to launch. Table I and II represent the power requirement budget each mode and mass budget, respectively. Fig. 3 indicates the HAUSAT-1 coordinate system. Table III summarizes HAUSAT-1 specification.

Table III HAUSAT-1 System Specification

Item	Specification	Remark
Altitude	600 ~ 650(900) Km	TBD
Inclination	98 deg	TBD
Mass	< 1kg	Payload Included
Size	10 × 10 × 10 cm, Cubic	Payload Included
Power	> 1.5W	@EOL
Accuracy	< 10 deg	
Payloads	Spaceborne GPS Receiver Solar Panel Deployment Mechanism Sun Sensor	
Downlink	1200 bps	FSK
Uplink	1200 bps	FSK
Mission Life	1 yr	

PAYLOAD SELECTION AND DESIGN

Three different payloads have been selected for the HAUSAT-1 satellite as follows; Solar Cell Deployment Mechanism (SDM), homemade sun sensor and spaceborne GPS receiver. The allocated mass and power for payload system are 160 g and 500 mW, respectively. Up to now, the estimated mass and power are 124.5 g and 500 mW, respectively.

SDM shown in Fig. 4 was selected to experiment on panel deployment mechanism in space. Through this space experiment, it will be verified that miniature torsion spring hinge works well within requirements. SDM should not make any interference with other hardware system and system operation. As soon as LTAN (Local Time of Ascending Node) is decided, the direction of SDM is also fixed. The HAUSAT-1 will be operated in the sun synchronous orbit, which means the HAUSAT-1 can generate more power when SDM is deployed into right direction in accordance with LTAN.

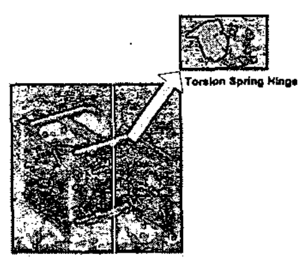


Fig. 4 Solar Cell Panel Deployment Mechanism

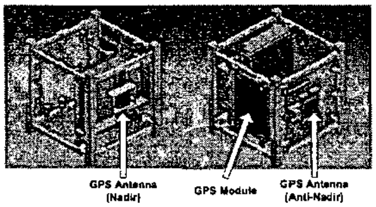


Fig. 5 Location of Spaceborne GPSR and Antenna

The HAUSAT-1 will obtain the position data from NORAD TLE data and integrated sensor data. GPS receiver can be also used to get the satellite position data. The spaceborne GPSR should be adapted to high speed satellite, and to have low mass and power dissipation. Especially, spaceborne GPSR system should have the frequency-error-correction-function by Doppler Effect and short data reacquisition time. The GPS specifications required for the HAUSAT-1 are as followings; speed of 8 km/s, less than 1s data reacquisition time, and 16 meter 2DRMS. Allstar of CMC Electronics is selected for the HAUSAT-1 GPS. In the case of HAUSAT-1, nadir and anti-nadir direction antennas are switched per half of orbit cycle. This situation is originated by using permanent magnet used for attitude control system. After all, the HAUSAT-1 incorporates two GPS antennas into two opposite directions, Nadir and Anti-Nadir, as shown in Fig. 5.

The HAUSAT-1 is also implementing homemade sun sensor. The sun sensor was designed and manufactured by SSRL students. The configuration of sun sensor assembly is shown in Fig. 6. After verifying this sensor in space, it will be adopted for HAUSAT-2 which is a 20Kg class nanosatellite.

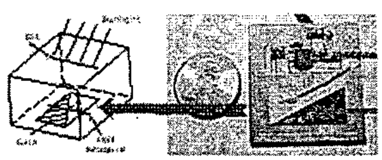


Fig. 6 SSRL Homemade Sun Sensor

SPACECRAFT BUS DESIGN

Structure and Mechanism Subsystem (SMS)

The HAUSAT-1 is a picosatellite weighing less than 1kg with 10cm × 10cm × 10cm cubic configuration. There are important factors in considering the design of the HAUSAT-1 structure and deployment mechanism; efficient distribution of internal space, satisfaction of constrained weight requirements, simplicity of deployment mechanism, and securing of reliability.

Aluminum 6061 is used as structural material. HAUSAT-1 structure can be classified as primary and secondary structure. The bolts and nuts are used to combine each structure. For efficient support of internal subsystem board, each board is fixed on internal panel using bracket and fastener. The structural configuration for securing work space is provided for manufacturing, assembly and test.

As shown in Fig. 7, The HAUSAT-1 satellite consists of four vertical beams, eight horizontal beams, six side panels, main board guard, subsystem board bracket, and battery case, etc. Each component is connected to bolts and nuts and then covered with epoxy to enhance strength during vibration test and launch. Two holes are made on the front panel to provide flight switch for ground test of satellite and port for accessing data. The hole size is 35mm × 20mm. Fig. 8 presents real HAUSAT-1 QM model which consists of four PCBs interfaced with pin harness.

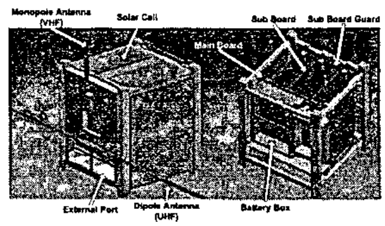


Fig. 7 Internal and External View

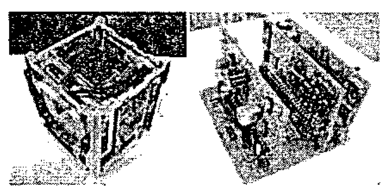


Fig. 8 HAUSAT-1 QM Model

Electrical Power Subsystem (EPS)

The HAUSAT-1 EPS is composed of solar panel, battery pack, power regulation and power distribution circuits. The purpose of EPS is to supply power stably having 3.3V and 5V. The power distribution is controlled by the on-board computer. Fig.9 describes EPS system block diagram.

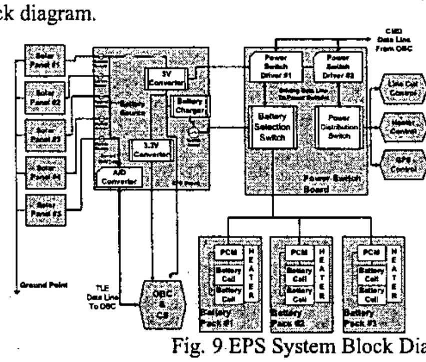


Fig. 9 EPS System Block Diagram

The HAUSAT-1 has five solar panels except nadir panel. One of these shall be deployed. Two solar cells on each panel form one string. 4×7 cm CIC 21% Ga-As is selected, which generates 4.1V power. The direction of deployable panel is selected according to decision of LTAN to generate the maximum power.

Three battery packs are implemented to supply power during eclipse time. One pack consists of two battery cells which interface with parallel and one PCM (Protection Circuit Module). The cell is ICP633450 940mAh Li-Ion made in LG Chemical. The PCM protects overcharge, overdischarge and overcurrent, and informs voltage, current, and accumulated current in battery.

Using MAX1708 step-up converter and MAX1685 step-down converter, the bus voltage of 3.6V is converted into 3.3V and 5V required for subsystems. On-chip PWM SMPS is used as power conversion method. To cope with variation of battery and solar cell output voltage, all input power is first converted 5V and then 3.3V is made. It allows more stable output power. Converting efficiency is 92% and 88% in 5V and 3.3V, respectively.

PDU (Power Distribution Unit) is controlled by OBC. PDU consists of MAX395 8 channel SPST ICs for SPI communication which is main communication method in HAUSAT-1. Fig. 10 illustrates EPS EM board.

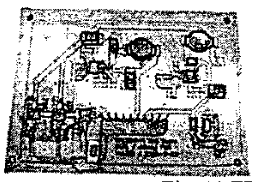


Fig. 10 EPS EM Board

Communication Subsystem and Ground Station (CS & GS)

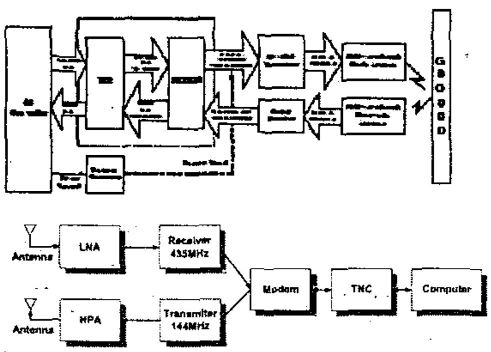


Fig. 11 Communication / Ground Station Flow Diagram

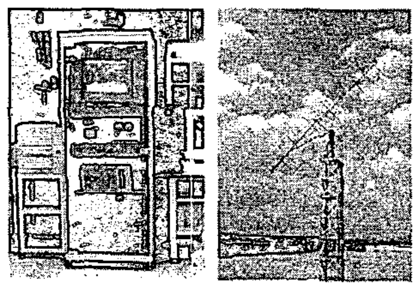
The frequency used for communication subsystem should be highly reliable, and little traffic. By using HAM frequency, HAM can support to find out the position of satellite. It is hard to track the picosatellite on the ground station because of small size and the signal transferred with lower power compared to other conventional satellites.

The communication subsystem of the HAUSAT-1 consists of transmitter, receiver, TNC (Terminal Node Control) including modem, and antenna.

All electrical modules of the HAUSAT-1 communication subsystem were designed and manufactured with SSRL's own technology to meet mass and power design budget.

It should be also considered to use the amateur band and HAM without interference from other HAMs in manufacturing the communication modules.

Since the HAUSAT-1 is so small and cannot generate high power from the solar cell, it definitely reveals the weakness point in the communication subsystem. The receiving power is weak on the ground station, on the contrary the transmitting power should be strong. The receiving traffic could be recovered by the transmitting power. The HAUSAT-1 selected 145.84 MHz for uplink and 435.84 MHz for downlink, amateur J mode, whose frequency is HAM bandwidth. The ground station has been designed and constructed based on the configuration of AMSAT standard ground station. Fig. 11 shows the communication and ground station flow diagram, respectively.



Ground Station **Cross-Yagi Antenna**

Fig. 12 Ground Station and Antenna

Fig. 12 shows ground station console and antenna constructed on house-top of engineering building. The station console consists of following equipments; IC-910H transceiver by ICOM having output of 100W and 75W on 144Mhz and 430MHz, respectively, Kantronics KPC-9612+ which is capable of conducting packet communication, HL-350VDX Power Amplifier having up to 300W, Rotator Controller and Interface Card, and GSV-3000 Power Supply.

The antenna can track satellite automatically by installed rotator. It is controlled by Kansas City Tracker Interface card. The ground station is also able to correct Doppler Effect automatically. The antenna illustrated in Fig. 12 was donated by High Gain Antenna Corp. in Korea.

The frequency registration procedure has been completed as shown in Fig. 13. The signals from some cubesats, which were launched last June 30th, such as "XI" (University of Tokyo) and "Cute" (Tokyo Institute of Technology) and AMSAT were successfully received by automatic tracking. This test operation has verified our ground station design and construction for the readiness of communication with HAUSAT satellite.

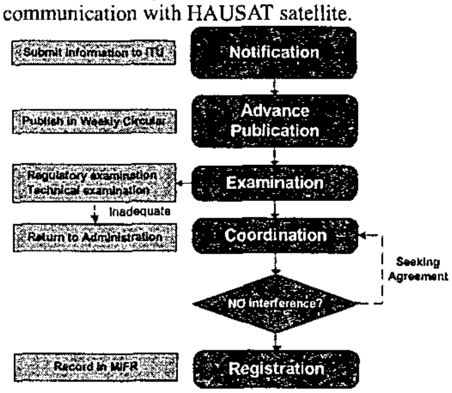


Fig. 13 Frequency Registration Procedure

Attitude Determination and Control Subsystem (ADCS)

The external disturbances are caused in orbit by space environments such as magnetic field, gravity gradient, solar pressure and atmosphere. Various disturbances can occur at the same time. The magnitude of magnetic field disturbance is the most predominant in the case of HAUSAT-1 as shown in Table IV. Therefore, ADCS system design of the HAUSAT-1 was focused on controlling magnetic field. Table IV presents major disturbance torque calculation results exerting on the HAUSAT-1.

Table IV Disturbance Torque

Type of disturbance	Max. torque (N-m)
Magnetic field	1.036 × 10-6
Gravity field	2.112 × 10-10
Solar pressure	8.170 × 10-10
Atmosphere	4.000 × 10-10
Total disturbances	1.037 × 10-6

The key point of the HAUSAT-1 ADCS design is associated with low power generation, low pointing accuracy (10 degree) requirements and low mass budget. HAUSAT-1 selected passive attitude control system which is simple and relatively reliable. The HAUSAT-1 ADCS was originally designed considering active three axis control method with the implementation of magnetometer and three magnetic coils. We decided to change the active control into passive control to ensure simplicity and better reliability. Its change is based on the lessons learned from some cubesat failures launched on June 30th, 2003.

Permanent magnet and hysteresis rod as a damper are incorporated to control HAUSAT-1. If the satellite would have some magnetic properties, it could align itself in the direction of the field. If one consider the Earth as a giant bar magnet, then another bar magnet attached to HAUSAT-1 will try to point towards the direction of the opposite pole of the Earth. Finally the satellite can fly parallel to magnetic field.

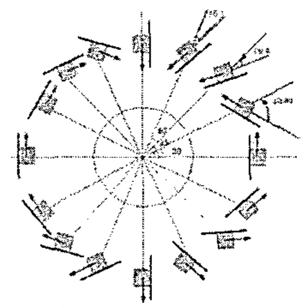


Fig. 14 HAUSAT-1 Attitude Aspect during One Orbit

Fig. 14 shows stabilization during one orbit. HAUSAT-1 will be spinning two revolutions every orbit. HAUSAT-1 uses a hysteresis rod to control tumbling. The rod makes Eddy Current that is orthogonal in earth magnetic line. Eddy current interrupts rock from side to side, which results in stabilization of HAUSAT-1.

The passive attitude control system using permanent magnet and hysteresis rod is very simple and more reliable. Table V presents permanent magnet and damper specification selected for HAUSAT-1.

Table V Permanent Magnet and Damper Specification

Permanent Magnet		Damper
Alinco-5	Material	49%Permalloy
2×3×55	Size (mm)	0.35×35×85
2	Mass (g)	8
2.82×10^{6}	Torque (N-m)	1.58×10^{6}

The simulation study has been performed with permanent magnet and hysteresis rod. Initial attitude of satellite angles are assumed to be $\phi=1^\circ,\theta=1^\circ,\varphi=1^\circ$.

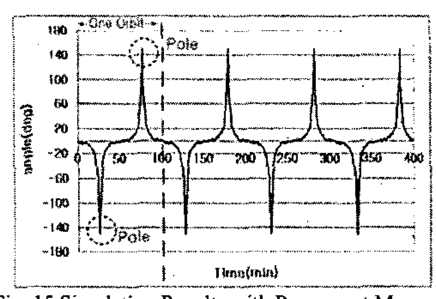


Fig. 15 Simulation Results with Permanent Magnet and Hysteresis Rod

Fig. 15 shows results of simulation during five orbits.

HAUSAT-1 maintains stabilization for 15 minutes, but after that HAUSAT-1 is tumbled for about 10 minutes, because HAUSAT-1 passes over North and South Poles. However, HAUSAT-1 will be stabilized except for two poles.

On-Board Computer Subsystem (OBC)

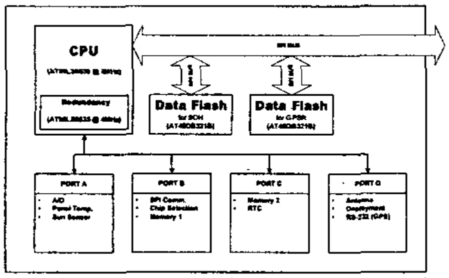


Fig. 16 OBC System Diagram

The OBC is one of the important systems because the OBC manages and controls the whole system of the HAUSAT-1. The OBC consists of a microcontroller, Analog to Digital converter, memory, and so on. Fig. 16 represents OBC system block diagram which has four ports with eight I/O pins. Each port is classified functionally as follows; the port A is for sensing, the ports B and C control data communication and manage mass storage memories, and the port D is assigned for payload system and mechanical operations. The OBC is capable of storing 64Mbits of SOH and payload data.

Table VI Acquired Data

Subsystem	Sensor Type	Qty	Sampling Rate [Hz]	Word Size [bit]	Data Rate [bps]
EPS	Voltage	9	1/2th	12	54
	Current	10	1/2th	12	60
	Batt. Temp.	3	1/2th	11	16.5
	Fuel Gauging	3	1/2th	12	18
OBC	OBC Status	1	1/2th	8	4
	EPS Status	1	1/2th	8	4
	CS Status	1	1/2th	8	4
	Payload Status	1	1/2th	8	4
	Etc.	1	1/2th	8	4
PAYLOAD	GPS	1	1	616	616
	Sun Sensor	8	1/2th	10	4
TCS	Panel Temp.	3	1/8th	8	3
Total Data Rate (per sec)					791.5
Daily Data Rate (Mbit)					68.3856

The HAUSAT-1 is designed to implement fault-tolerant system architecture based on ATMEL AVR 8bit controller allowing SPI communication bus. The HAUSAT-1 incorporates redundancy to provide fault-tolerant system. Redundancy is necessary aspect of fault-tolerant system, because a fault-tolerant system must function correctly even after some of its elements have failed.

Fig. 17 represents HAUSAT-1 fault-tolerant system steps. System reset occurs depending on watchdog timer and subsystem status. In software redundancy step, flight software is reloaded or replaced with new software. In step 3, system architecture is changed to new architecture design depending on individual case. Step 4 shows system degradation (graceful degradation), which is an important feature, closely related to fault-tolerant system. Graceful degradation is simply the ability of a system to automatically decrease its level of performance to compensate for hardware and software faults.

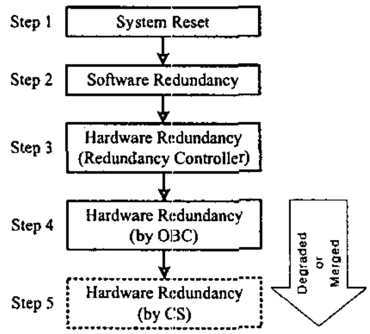


Fig. 17 Fault-Tolerant Step

Thermal Control Subsystem (TCS)

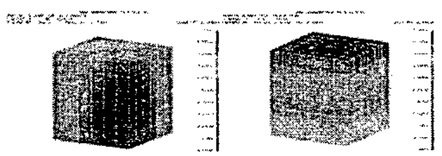
The purpose of the TCS is to maintain all satellite components within their specified temperature limits throughout all mission phases. There are some ways to protect satellite from harsher thermal environment; passive and active methods. Because of limited mass and power budget, the HAUSAT-1 must accomplish heat control, making the utmost use of passive method as internal heat conduction, surface finish and body mounted radiator well. Typical temperature ranges allowed for satellite components are given in Table VII. The basic equations of satellite thermal equilibrium can be expressed as follows [9];

$$q_{Solar} + q_{Albedo} \bullet q_{Earth} + q_{Int.Heat} - q_{Emiteed} = 0$$

Based on this equation, the steady state thermal analysis and transient analysis have been accomplished. In these analyses, the assumptions were that deep space temperature is 3K and the satellite structure material is Al-6061. As shown in Fig. 18, the maximum and minimum temperatures during sunlight and eclipse are about 28.38°C and -27.85°C, respectively. Fig. 19 shows board level thermal analysis results. The maximum and minimum temperatures are 31.83°C in hot case and -41.97°C in cold case, respectively.

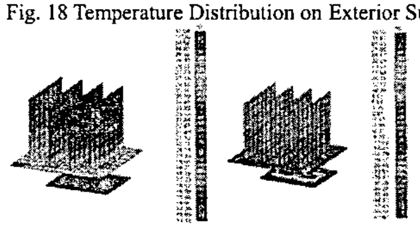
Table VII Temperature Range of Components

Component	Operating Temperature Range	Survival Temperature Range
Battery	0 to 40	-20 to 60
Solar Cell	-30 to 30	-100 to 100
Kapton Heater	-200 to 200	-200 to 200
Electronics	-25 to 55	-40 to 80
GPS Receiver	-35 to 75	-55 to 90
GPS Antenna	-30 to 85	-40 to 90



(a) Hot Case (b) Cold Case

Fig. 18 Temperature Distribution on Exterior Surface



(a) Hot Case (b) Cold Case

Fig. 19 Board Level Thermal Analysis Results

It is assumed that the solar flux illuminates on the right corner of the satellite, and the satellite bottom surface always orients toward the nadir. It is supposed to be difficult to operate the HAUSAT-1, in particular, the battery module without the additional thermal control. The heater is inevitable to protect the battery from cold temperature. Fig. 20 shows the transient temperature analysis results. The estimated satellite temperature has the range between -21°C to 20°C and varies periodically according to sunlight time and eclipse time.

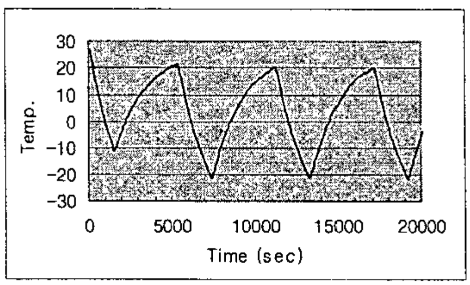


Fig. 20 Transient Analysis

By comparing these analysis results to the temperature requirements of the components in Table VII, it was found that some components like battery are not within the specified limits. Additional thermal control may be required for these components by using MLI, heater, thermal isolator to satisfy their temperature limits. Based on these analysis data, we selected proper surface coating material for the HAUSAT-1 and helped lay out the satellite components.

Flight Software

Flight Software (F/S) is coded with IAR Embedded Workbench C Complier for AVR. F/S is classified into five groups as system timer, acquiring data, data storage, internal communication with Serial Peripheral Interface (SPI) and Universal Asynchronous Receiver and Transmitter (UART), and interrupt routine. System timer uses internal timer and other timer related to sampling rate is synchronized by timer match interrupt.

All functions are modularized to avoid code duplication and reduce code size. It allows that correction of code is easy and program reconstruction is feasible.

ETB ASSEMBLY AND TEST

The purpose of ETB test is to demonstrate that all functions of the HAUSAT-1 electrical boards work properly. This test is used to verify that system level requirement are met and F/S operates well. It also characterizes other parameters such as impedance, waveforms, etc. ETB consists of test modules, instruments and equipment, and workstation for data analysis and record. Electrical boards which are tested are consisted of three sub-boards, GPS board, main board and external port board. The commercial bench-top instruments such as oscilloscope, logic analyzer, spectrum analyzer, etc. are used rather than designing EGSE (Electrical Ground Support Equipment).

The ETB test is accomplished in SSRL Clean Room considering contamination control and ESD protection. SSRL Clean Room maintains 60~70% humidity and 18~20°C temperature. ETB test is progressed in order of following test; individual module test, system integration full functional test and end-to-end test with ground station. Fig. 21 shows ETB assembly.

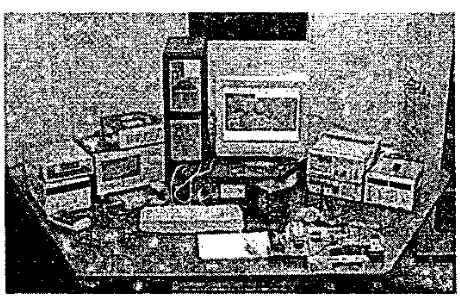


Fig. 21 ETB Assembly

CONCLUSIONS

The purpose of the HAUSAT-1 project is to offer graduate and undergraduate students great opportunities to be able to understand the design process of satellite development as a team member. Its mission objectives are collecting the satellite position data with spaceborne GPS receiver, experiment on deployment mechanism of solar cell panel and homemade sun sensor, and getting data related to satellite state of health from various sensors. It will be verified through the HAUSAT-1 operation that a picosatellite a means of low cost access to space for technology demonstration.

Several trade-off studies have been carried out during the development and design. The selection and sizing studies for most components were completed. The preliminary structure and thermal analyses at the system level have been accomplished. The power and attitude control simulation were also performed to select the optimal power and attitude control architecture for picosatellite. An optimal architecture at the subsystem levels have been finalized based on the simulation and analyses results. ETB (Electrical Test Bed) has been assembled and tested to ensure the functionality of HAUSAT-1 system and the flight software. Presently QM (Qualification Model) is being manufactured, fabricated and tested for design margin and environmental verifications.

The HAUSAT-1 FM (Flight Model) will be completed until the end of this year to be ready for next year's launch.

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