Development of HAUSAT-1 Picosatellite Communication Subsystem as a Test Bed for Small Satellite Technology

Byoung-Young Moon*, Young-Hyun Kim* and Young-Keun Chang**
School of Aerospace & Mechanical Engineering
Hankuk Aviation University, Goyang-City, Korea 412-791

Abstract

This paper addresses the development and design of the HAUSAT-1 (Hankuk Aviation University SATellite-1) communication subsystem, which is a next generation picosatellite, developed by SSRL (Space System Research Lab.) of Hankuk Aviation University. The communication subsystem generally consumes the majority of power and volume for picosatellites, and thus its design is critical to the overall satellite and mission plans. The HAUSAT-1 designs are implemented by using the 145.84 MHz for uplink and 435.84 MHz for downlink frequency bands. The simulation and test results of the homemade radio and the TNC (Terminal Node Controller) integrated on the HAUSAT-1, a picosatellite scheduled to launch on September 2004 by Russian launch vehicle "Dnepr", are presented for EM, QM and FM, respectively.

Key Word : CubeSat, Communication Subsystem, TNC, MODEM, HAUSAT-1

Introduction

CubeSat & HAUSAT-1 Overview

The CubeSat program was initiated by Cal Poly and Stanford University to involve students in the development of small satellites of ~1kg mass with 10cm x 10cm x 10cm cubic configuration to perform experiments of limited scope at greatly reduced cost. The first six CubeSats were already were launched on June 2003, some CubeSats are still conducting their mission until even now.

Students at the Space System Research Laboratory (SSRL) in Hankuk Aviation University have joined this international program and completed the development of three different models, such as EM (Engineering Model), QM (Qualification Model), and FM (Flight Model). SSRL is one of the National Research Laboratory (NRL) awarded by Ministry of Science and Technology (MOST) in Korea to contribute space core technology development. The HAUSAT-1 (Hankuk Aviation University SATellite-1) is scheduled to launch by a Russian Dnepr(SS-18) launch vehicle in September 2004. The primary objective of HAUSAT-1 satellite development is to offer graduate and undergraduate students opportunities and to 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 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 (State of Health) from various on-board sensors, whose data are being used to develop the HAUSAT-2

---

* Graduate Student
** Professor
E-mail : ykchang@mail.hau.ac.kr, Tel : 02-300-0286, FAX: 02-3158-3189

nanosatellite.

The basic goal of HAUSAT-1 picosatellite system is to produce a baseline design upon which further development can be made as a test bed for improved small satellite technologies.

The Communication Subsystem Design

HAUSAT-1 Communication Subsystem Specification

The communication subsystem will be responsible for performance when the satellite is in a communication window. At such times, the communication should transmit telemetry data to the ground station and receive commands from the ground station. The specification establishes the design, construction, performance, development, and test requirements for the communication subsystem of the HAUSAT-1 satellite.

The communication subsystem functionally consists an antenna, radio (RF section), and TNC. The communication subsystem will packetize data using the AX.25 protocol to transmit data. It will then modulate, amplify, and transmit a RF signal. While receiving data, the communication subsystem will demodulate a RF signal and then detect the received Dual Tone Multi Frequency (DTMF) signal.

The major requirements for HAUSAT-1 communication subsystem are in Table 1.

Table 1. Communication Subsystem Requirements

Frequency	Downlink	435.84 MHz
	Uplink	145.84 MHz
Communication Method	NBFM	
Band Width	< 20 kHz	
Protocole	AX.25	
Data Rate	1200 bps	
Output Power Level	Packet	More than 500 mW
	Beacon	More than 100 mW
Sensitivity	More than -90 dBm	
Mass	35 g	
Volume	86 mm x 60.5 mm x 20 mm	
Margin	More than 3 dB	
Impedance matched to the HPA and LNA		
Transmitter (with HPA), Receiver (with LNA) and DTMF shall occupy a board, CS Board TNC must occupy a part of the CS-PDU board		
Beacon transmission for tracking and receiving basic telemetry and SOH		
Withstand environmental stresses of the launch and space environment		

Fig. 1 describes HAUSAT-1 communication subsystem functional block diagram which shows how each component of the communication subsystem interacts with major components of the communication subsystem. The communication subsystem should interface with the On-Board

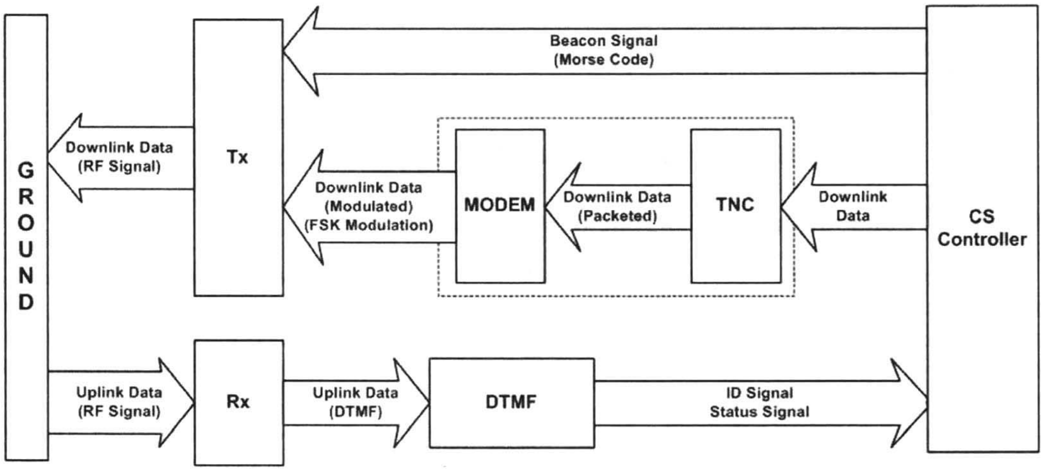

Fig. 1. Communication Subsystem Functional Block Diagram

Computer (OBC) via SPI communications, the Electrical Power Subsystem (EPS) via 3.3V, 5V and GND power lines, and the Ground Station (GS) via a wireless communications link.

Hardware

The conceptual design of HAUSAT-1 was to implement a modified COTS (Commercial-off-The Shelf) TNC with a handheld transceiver. Unfortunately, it is realized that the COTS equipment which were considered didn't meet the required reliability, and were difficult to modify for space flight. After evaluating several options, the only viable solution was to design our own radio and TNC. By designing our own radio, we could also simplify the radio design. This simplification increases reliability and decreases the parts count, complexity and space of printed circuit boards.

Transmitter Part

The transmitter part is composed of transmitter, amplifier and Tx antenna as shown Fig. 2. The sufficient power has to be supplied for the transmitter part to communicate with the ground station during the whole communication duration which is estimated to be more than 500 mW (about 27 dBm).

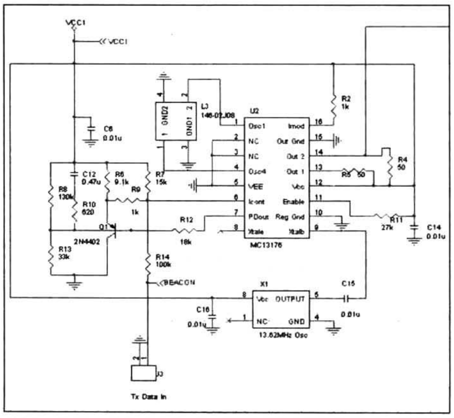

Fig. 2. Transmitter Schematic Diagram

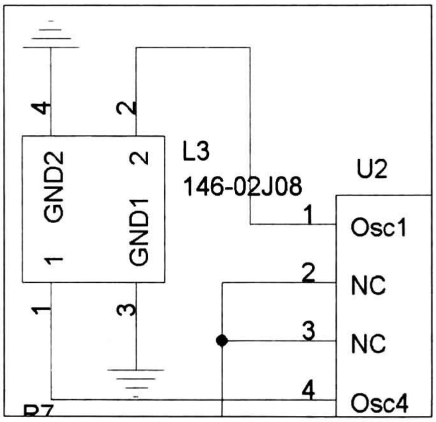

Fig. 3. Current Controlled Oscillator

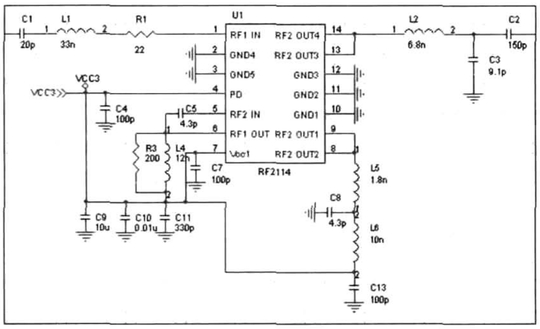

Fig. 4. HPA Schematic Diagram

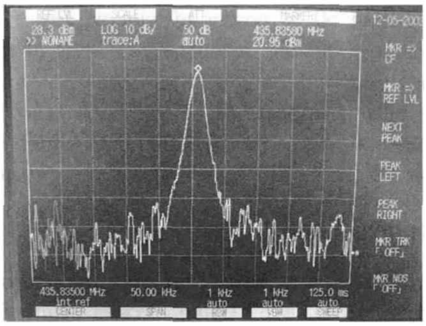

Fig. 5. Transmitter Output

The transmitter should generate a RF signal in the input range of the HPA (High Power Amplifier) and operate FM transmission method. MC13176 which is Motorola FM transmitter chip has been used for the HAUSAT-1. The transmitter chip is including a Colpitts crystal reference oscillator, UHF oscillator, ÷32 prescaler and phase detector forming a versatile PLL system. Targeted applications are between 260 and 470 MHz frequency bands and the HAUSAT-1 transmitter generates the RF signal to communicate data from the satellite to the ground station within the 435.84 MHz frequency UHF band. In order to successfully transmit, the chip must have a stable crystal oscillation and suitable RF Coil (Inductor) for frequency locking. It may be operated with either a fundamental or overtone crystal depending on the carrier frequency and the internal prescale. Current Controlled Oscillator (Pin 1, 4 and 6) shown in Fig. 3, Phase Detector (Pin 7), generate 453.84 MHz RF signal and a variation of input current which is branched to pin 6 with 100 kΩ resistance (R14) makes FM Modulation within 4.5 kHz.

The transmitter antenna should transmit within the 70cm UHF band radio frequency signal and has omni-directional beam pattern into azimuth direction. A 35cm dipole antenna whose impedance is matched to the amplifier (RF2114 HPA chip) has been designed.

The MC13176 transmitter chip can only generate a maximum of 14 dBm power. This is not enough power to successfully transmit to the ground station. The signal must be amplified to more than 27 dBm (0.5 Watt) in order to establish a reliable communication link. Since the signal power from transmitter ranges from -4 to 10 dBm, the amplifier should be able to boost a -4 dBm signal up to 30 dBm, which is equivalent to about 26 to 27 dB gain. Thus, the amplifier must have more than 26 dB gain and be more than 50 % power efficient. The communication subsystem incorporates an amplifier (RF2114, RF Micro Device). The amplifier which is described on Fig. 4 can be operated at 435.84 MHz which will be used for the HAUSAT-1 and have approximately 27 dB gain with

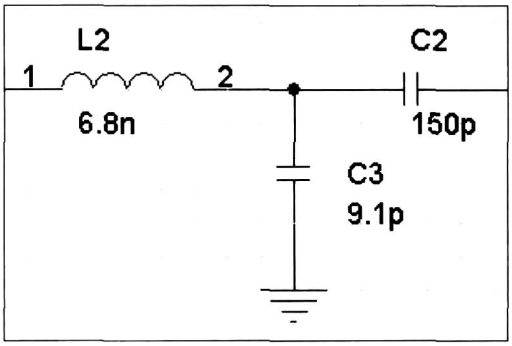

Fig. 6. HPA Output Schematic Diagram

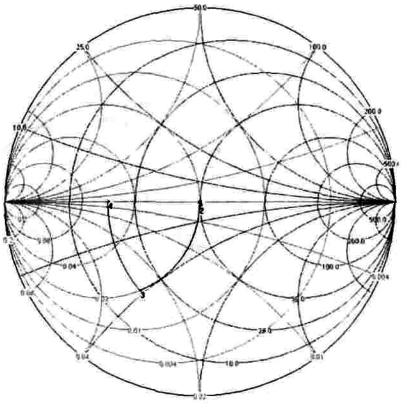

Fig. 7. HPA Matching within 18+j0

more than 50 % power efficiency. Fig. 5 describes an output spectrum which displays the output frequency and the output power level of the HAUSAT-1 transmitter within the HPA. Specially, the impedance matching between the HPA and the Tx antenna is important for maximum output level. The output impedance of the HPA (Pin 14) which is 18+j0 Ω matched to 50 Ω. Fig. 6 describes placements of the passive elements which is calculated by the smith chart for the impedance matching (Fig. 7). The size, mass, and temperature tolerance of this device meet the requirements.

Receiver Part

The receiver part of communication subsystem functionality consists of an antenna, radio (receiver), DTMF (Dual Tone Multi-Frequency) receiver and LNA (Low Noise Amplifier, Pre-Amplifier) which are describe in Fig. 8. In order to receive command, the satellite has to receive a FM signal and recognize DTMF Signal.

A receiver-on-a-chip, MC13135, has been used for the HAUSAT-1. The parts number of count and complexity of the radio can be reduced by using a single-chip receiver. The single-chip receiver, MC13176, 15.01555 MHz TCXO for local oscillator and the single chip LNA provide good sensitivity, selectivity, a wide temperature range (-40 to +80℃), and low power consumption.

The low external parts count shown in Fig. 8 is an additional benefit of using these ICs. MC13135 is dual conversion FM communications receiver. It receives the RF signal to communicate data from the ground station to the satellite in the 145.84 MHz frequency VHF band. The MC13135 includes a Colpitts oscillator, VCO tuning diode, low noise first and second mixer, local oscillator, high gain limiting IF, and RSSI. The MC13135 is designed to use with a LC quadrature detector. Targeted applications are in the VHF band.

The RF signal will mix with the 9th overtone circuit (135.14 MHz) which TCXO (15.015555 MHz) pin 1 is used. Fig. 9 describes that two overtone stages for 135.14 MHz. In first stage, 15.015555 MHz frequency is multiplied by three. Similarly the frequency from first stage is multiplied by three in second stage. The product frequency 10.7 MHz (145.84 MHz - 135.14 MHz) will come out of pin 20. A ceramic filter removes all other frequencies except the 10.7 MHz which enters at pin 18. On pin 5 and 6, 10.7 MHz signal meets a new mixer which mixes the 10.7 MHz with another crystal oscillator (10.245 MHz) pin 5 and 6. So then The frequencies 455 kHz (10.7

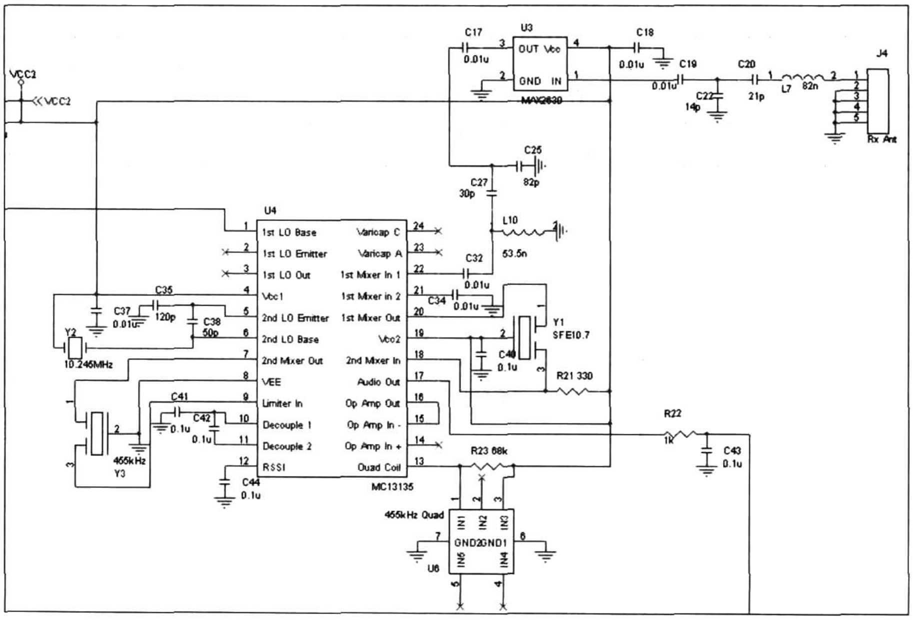

Fig. 8. Receiver Schematic Diagram

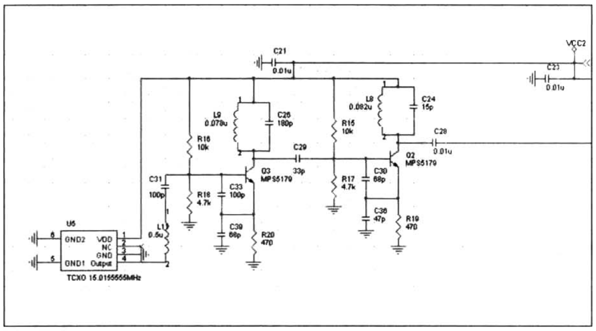

Fig. 9. 1st Local Oscillator within 135.14 MHz

MHz - 10.245 MHz) will come out of pin 7. A ceramic filter removes all other frequencies except the 455 kHz which entered pin 9. This tiny signal at 455 kHz which will vary a little around 455 kHz depending on the FM-modulation (+/- some kHz) must be amplified to a level where the audio signal can be demodulated from the RF signal.

At pin 13 and 14, a ceramic filter or a "quad coil" is connected. This component will bring out the sound from the 455 kHz IF signal. At pin 17 the recovered audio signal is amplified to 200mV. Finally, input stage (Pin 22) is matched into 720 kHz which is described Fig. 10.

Fig. 11 describes the output wave form which is simulated in -95 dBm input level.

The DTMF receiver must recognize a DTMF signal within 0~9, A~D, * and #. It also has the ability to set a enough rate and output 4-bit code (form pin xx to pin xx) within hex-decimal. The HT9170 is Dual Tone Multi Frequency (DTMF) receiver which is integrated with digital decoder and band-split filter functions used in Receiver Part. All types of the HT9170 series use digital counting techniques to detect and decode all the 16 DTMF tone pairs into a 4-bit code output.

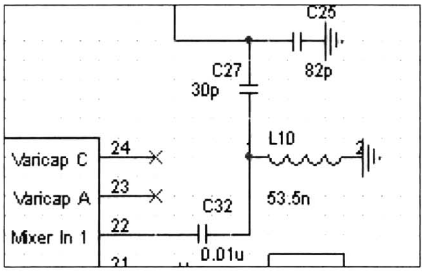

Fig. 10. Receiver Output Matching Schematic Diagram

The pre-amplifier should have low noise amplification (less than 5dB noise figure) and more than 13 dB gain. The MAX2630 is broadband amplifier with 3dB bandwidth greater than 1GHz. Their small size and internal bias circuitry make them ideal for applications where board space is limited like receiver of HAUSAT-1 within 145.84 MHz. The MAX2630 is easy to use input and output series capacitors may be necessary to block DC bias voltages generated by the amplifiers from interacting with adjacent circuitry. These capacitors must be large enough to contribute negligible reactance in a 50Ω system at the minimum operating frequency. Following equation is used to calculate their minimum value:

$$C_{BLOCK} = \frac{53000}{f}[pF] \tag{1}$$

where f (in MHz) is the minimum operating frequency.

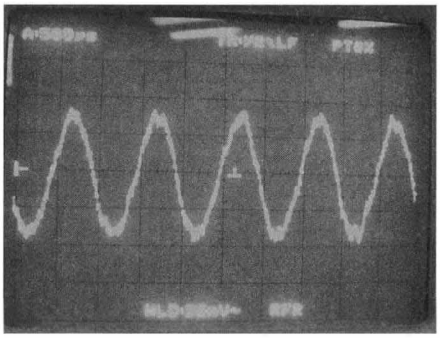

Fig. 11. Audio Output within 4.5kH dev.

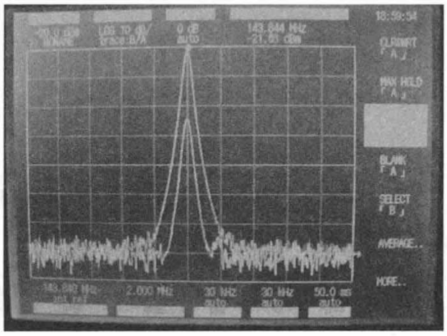

Fig. 12. Low Noise Amplifier Gain

The LNA which is implemented in the HAUSAT-1 receiver has 13.6 dB gain which is described in Fig. 12.

The antenna of the receiver part has to receive within the 2 m VHF band radio frequency signal and has omni-directional beam pattern into azimuth direction. One meter monopole antenna has been implemented for Rx Antenna whose impedance is matched to the amplifier (MAX2630). Antennas of HAUSAT-1 Tx and Rx are described in Fig. 13.

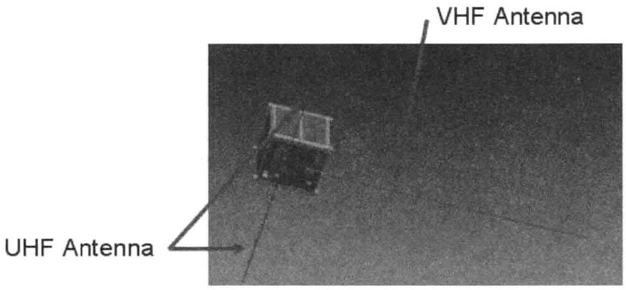

Fig. 13. Tx Antenna for UHF and Rx Antenna for VHF

TNC (Terminal Node Controller) Part

For a reliable telemetry data communication, the HAUSAT-1 contains a low speed (1200 bps) TNC part. Because of the inadequacy and size overhead of commercial systems, we decided to make our own custom TNC. The TNC part of communication subsystem functionality consists of a the TNC and the MODEM. Each Fig. 14 and Fig. 15 describe the TNC and MODEM, respectively.

The TNC connecting the microprocessor which is a PIC16F873 using RS-232 serial communication to the receiver handles AX.25 packet protocol for the data communication. Its function is similar to those of a normal analog computer modem. It converts the digital signals received from the computer to analog signals send to the radio and also the other way around for analog signals from the radio.

The MODEM modulates a 1200 baud AFSK (Audio Frequency Shift Keying) signal. The serial bit stream is provided to the microprocessor which processes the packet radio data. A FX-614 FSK MODEM chip is used for main component for a modulation.

The AX.25 protocol was implemented to guarantee the reliability of the communication link. The AX.25 protocol was chosen due to following reasons,

- Supports amateur call names
- Supports connected links
- Supports half / full duplex
- Supports error detection

The AX.25 protocol envelops the data it sends to the physical layer in a frame. The structure of such a frame is shown in Fig. 16.

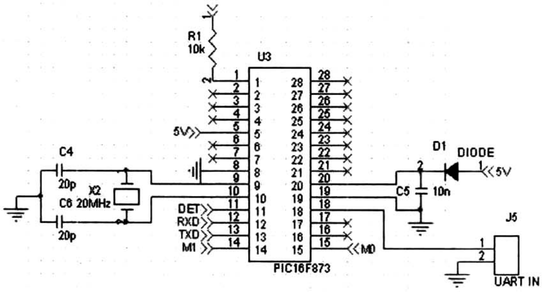

Fig. 14. TNC Microcontroller

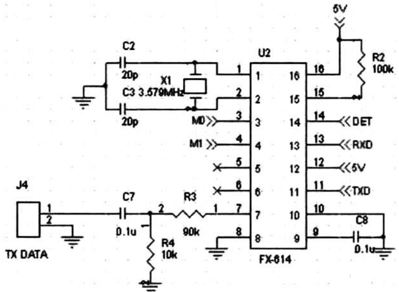

Fig. 15. FX-614 MODEM

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 bits	8/16 bits	8 bits	N*8 bits	16 bits	01111110

Fig. 16. AX.25 Frame

Since the packet radio is a bit-oriented protocol, the only certain way to tell with certainty when one frame ends and another begins is to delimit each frame with a specific bit sequence at both the beginning and the end. This is the job of the flag field. The address field uniquely identifies both the source and destination of the frame. Frames will only be accepted if both the destination and source address were matched those assigned to the satellite and ground station.

The HAUSAT-1 satellite was assigned a call sign, D90HP-1 and the SSRL ground station was identified as D90HP-0. The information field contains the data passed to the application layer. For uploaded frames, the information field contains a command. For downloaded frames, the information field contains data. The Frame Check Sequence (FCS) is a sixteen-bit number that is calculated by both the sender and receiver of a frame. Comparing the value computed by both the sender and receiver ensures that the frame was not corrupted by the transmission medium.

Link budget

The link budget is a survey of the elements in a radio communication. The link budget can often include the data rate and the quality for the modulation method so that the necessary Eb/No

Table 2. HAUSAT-1 Link Budget

(a) Uplink Budget

HAUSAT-1 Link Budget for Uplink			
Item	Symbol	Unit	Value
FREQUENCY	f	MHz	145.84
Tx Power	P	W	20
Tx Power	P	dBW	13.0103
Tx Line Loss	L_{lt}	dB	-3
TX antenna beamwidth	th_t	deg	37.4
Tx antenna peak gain	G_{pt}	dBi	12.8
TX antenna pointing error	e_t	deg	17
Tx antenna pointing loss	L_{pt}	dB	-3.185
Equiv. Isotropic Radiated Power	EIRP	dBW	19.6253
Propagation path length	S	km	2045.331
Space loss	L_s	dB	-141.833
Atmospheric loss	L_a	dB	-0.2
Polarization loss	L_{pol}	dB	-0.3
Rx line loss	L_{lr}	dB	-1
Rx antenna beamwidth	th_r	m	100
Rx antenna pointing error	e_r	deg	90
Rx antenna pointing loss	L_{pr}	dB	-9.72
Rx antenna diameter	D_r	dB	1.439934
Rx antenna peak gain	G_{rp}	dBi	-2.251
Rx system noise loss	L_n	dB	-31.1059
Data rate	R	bps	1200
Bit energy/noise ratio	Eb/No	dB	31.02359
Bit error rate	BER		0.00001
Req'd bit energy/noise ratio	$Eb/No_{(req)}$	dBHz	13.3
Implementation loss			-3
MARGIN		dB	14.72359

(b) Downlink Budget

HAUSAT-1 Link Budget for Downlink			
Item	Symbol	Unit	Value
FREQUENCY	f	MHz	435.84
Tx Power	P	W	0.5
Tx Power	P	dBW	-3.0103
Tx Line Loss	L_{lt}	dB	-1
TX antenna beamwidth	th_t	deg	110
Tx antenna peak gain	G_{pt}	dBi	2.148
TX antenna pointing error	e_t	deg	90
Tx antenna pointing loss	L_{pt}	dB	-8.033
Equiv. Isotropic Radiated Power	EIRP	dBW	-9.8953
Propagation path length	S	km	2045.331
Space loss	L_s	dB	-141.833
Atmospheric loss	L_a	dB	-0.2
Polarization loss	L_{pol}	dB	-0.3
Rx line loss	L_{lr}	dB	-1
Rx antenna beamwidth	th_r	m	29
Rx antenna pointing error	e_r	deg	15
Rx antenna pointing loss	L_{pr}	dB	-3.21
Rx antenna diameter	D_r	dB	1.439934
Rx antenna peak gain	G_{rp}	dBi	12.5
Rx system noise loss	L_n	dB	-25.7054
Data rate	R	bps	1200
Bit energy/noise ratio	Eb/No	dB	38.52565
Bit error rate	BER		0.00001
Req'd bit energy/noise ratio	$Eb/No_{(req)}$	dBHz	13.3
Implementation loss			-5
MARGIN		dB	20.24565

can be given and its margin can be estimated. Eb/No is the bit energy over the noise power density and is given by the transmission equation. Eb/No is the parameter which depends on the modulation type and is also the one that decides the bit-error-probability. A link budget has been computed using the methods described in SMAD$^{5)}$. Table 2 summarizes the results for each of the downlink and uplink.

Testing and Verification

Functional Tests with EM, QM and FM

The purpose of functional test is to demonstrate that all functions of the HAUSAT-1 communication subsystem work properly. This test is used to verify requirements are met. It also characterizes other parameters such as impedance, waveforms, etc. All functional tests are progressed in order of following diagram in Fig. 17.

The HAUSAT-1 was implemented three different models which are EM (Engineering Model), QM (Qualification Model), and FM (Flight Model). In the case of EM shown in Fig. 19, ETB (Electrical Test Bed) test were executed. Fig. 18 describes the communication subsystem ETB. During the ETB test, all functions and specifications were measured in details and requirements of the HAUSAT-1 were validated into measured values into details. All functional problems which was exposed during the ETB test was also corrected. The design which was

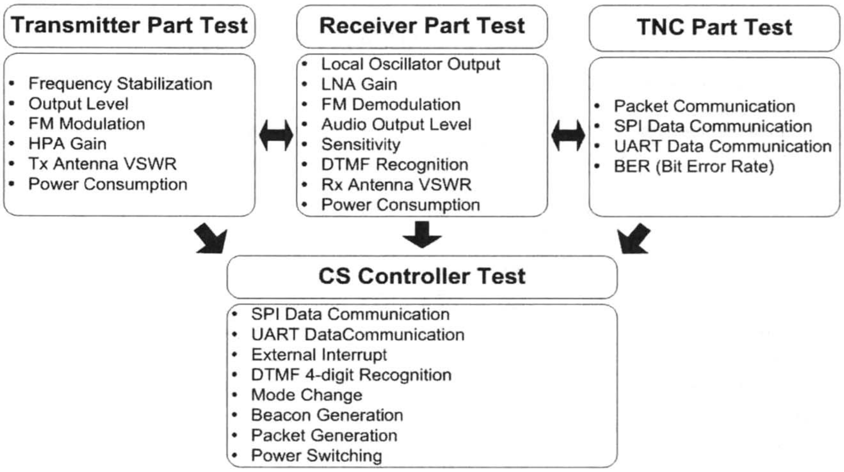

Fig. 17. CS Functional Test Organization and Contents

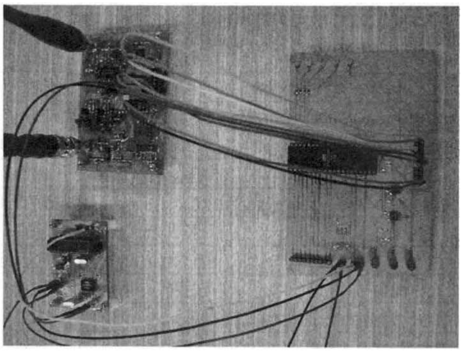

Fig. 18. CS ETB Set

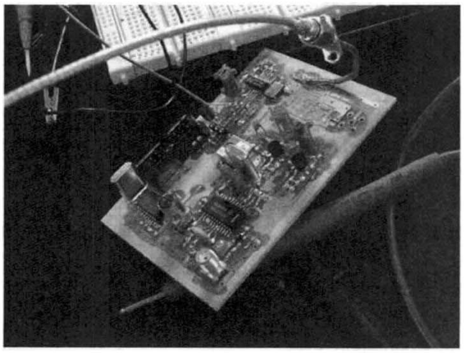

Fig. 19. CS Engineering Model

validated in the EM was reflected in the QM and the FM. The Functional tests also were executed in QM and FM in similar method of ETB.

The functional tests were accomplished in SSRL Clean Room by considering contamination control and ESD (Electro-Static Discharge) protection. SSRL Clean Room maintains 40% humidity and 20℃ temperature.

Communication Subsystem Environmental Tests

The HAUSAT-1 shall withstand environmental stresses of the launch. The electronics of the communication subsystem must work at extreme temperatures in vacuum. The vibration test and the thermal vacuum test were executed at the qualification level with QM (Qualification Model) of the HAUSAT-1 satellite.

In the vibration test, the sine-sweep test and the random vibration test were executed. The sine sweep tests were completed prior to random vibration tests for individual three axes for the modal survey. Table 3 describes the sine sweep vibration test level.

Table 3. Vibration Test Levels

Item	Test Level
G-Load Level	0.5 Grms (for the modal survey) 12.9 Grms (for the random vibration)
Sweep Speed	2 Oct/min
Sweep Range	20 ~ 2000 Hz
Duration	6 minutes for the sine sweep 1 minute for the random vibration

Fig. 20 shows the shaker at KOSPACE Co. LTD. in Kyungki-Do, Korea. The functional test were executed before and after the vibration test. It was found that the communication subsystem works normally after the vibration test.

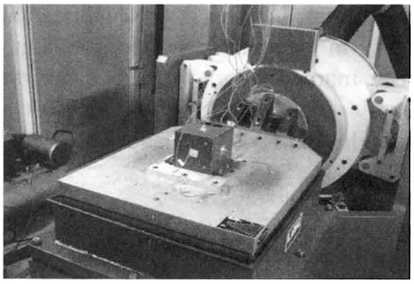

Fig. 20. Vibration Test

Fig. 21. Thermal Vacuum Test

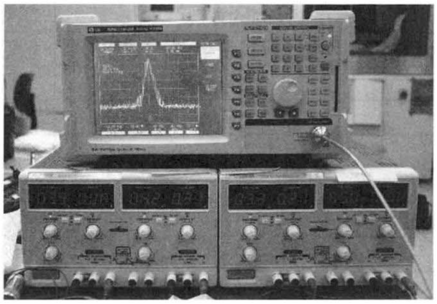

Fig. 22. TV Test Function Check

Table 4. Thermal Vacuum Test Level

Pressure	$5.0\times10^{-5}Torr$
Temperature Range	-30 ~ 70 ℃
Stability	± 1 ℃ in 120 Minutes
Duration	Soak : 20 Minutes Ramping : 20 Minutes
Cycle	2 Cycles

To find out if the designed communication subsystem will work in space, we have to test it under circumstances seldom experienced by commercial electronics. The tray was placed in a thermal chamber which is described in Fig. 21 and cycled from -30℃ to 70℃. Table 4 shows thermal vacuum test requirements in detail and functional test during thermal vacuum cycle are progressed as shown in Fig. 23. Equipment which included a spectrum analyzer, three DC power supplies, a handy transceiver and KPC-9612+ were set for the functional test. Fig. 22 describes these equipments.

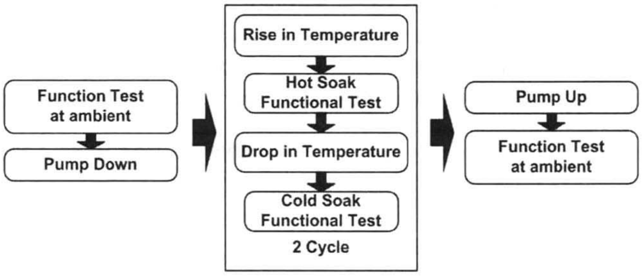

Fig. 23. Thermal Vacuum Test Procedure

Test Results

An optimal architecture at the communication subsystem levels have been finalized based on the simulation and analyses results. The ETB (Electrical Test Bed) has been assembled and tested to ensure the functionality of communication subsystem and the QM (Qualification Model) has been assembled and tested to ensure the functionality in extreme space environment. the FM (Flight Model) which is shown in Fig. 24 has also been manufactured, fabricated and tested for design margin and environmental verifications finally. Following Table 5 illustrates the comparison between requirements and test results highlight for EM, QM, and FM, respectively.

Table 5. Communication Board Specification

Item	Requirements	Performance
	Transmitter Part	
Frequency	435.84 MHz	435.8405 MHz
Frequency Stability	< △F(3kHz)	△F(1kHz)
Output Power	>0 dBm	0.15 dBm
Power Consumption	<650 dBm@3.3V	650 W @3.3V
Interface	TTL, Audio	TTL, Audio
HPA Gain	>27 dBm	27.12 dBm
Output VSWR	< 1:2 @50Ω	< 1:1.6 @ 50Ω
	TNC Part	
Packet Communication	AX.25	AX.25
BER	<10^-5	< 10^-5
Interface	ART, Audio	UART, Audio
Power Consumption	100 mW @3.3V	66 mW @3.3V

Receiver Part		
LNA Gain	>13 dB	13.6 dB
Input VSWR	< 1:2 @50Ω	1:1.5 @50Ω
Receiving Frequency	145.84 MHz	145.84 MHz
1st Oscillator Frequency	135.14 MHz	135.14 MHz
Sensitivity	< -90 dBm	-95 dBm
Power Consumption	< 200 mW	100 mW
Interface	Audio, P-Digit	Audio, P-Digit
DTMF Signal Detecting	0~9, A~D, #, *	0~9, A~D, #, *
Physical Specification		
Weight	<40g	39g
Dimension	86 mm x 60.5 mm	86 mm x 60.5 mm
Thickness	<1T	0.8T

The subsystem performance was accurately measured before and after environmental tests to detect any shifts in operation due to those tests. Especially, it is recognized that the frequency shift about -5 kHz occurred at hot soak condition, and about +5 kHz at cold soak condition after thermal vacuum test. That is, it is error of ±3 ppm which is with in TCXO manufacturing specification, and this problem can be solved by compensating the frequency when the ground station receives the signal.

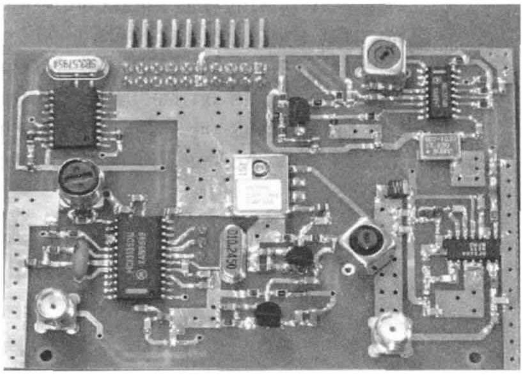

Fig. 24. Communication Board for FM

Conclusions

This paper has presented the design and development of the HAUSAT-1 communication subsystem. The selection of radio and antenna eliminated the overlooked power, mass, volume, and design difficulties of splitting, matching networks and antenna phasing which are required at the most design. Several trade-off studies have been carried out during the development and design. The selection and sizing studies for most components were completed. Tests and simulations indicate that this communication system meets the link and other requirements, while implementing almost entirely COTS and One-Chip-module.

The communication system which is presented here is already integrated for EM, QM, and FM. If it is as successful as our CubeSat communication subsystem design with requirements, it may be useful to the 70 cm and 2 m picosatellite system currently used. The approach presented here, of detailed RF and communications simulation can be directly applied to the design of HAUSAT-2 nanosatellite.

Acknowledgement

This study is supported by Core Space Technology Program and partially by National Research Lab. (NRL) Program funded by Ministry of Science and Technology. The authors would like to appreciate for the financial support.

References

1. Robert J, Twiggs, Hank Herdt, Jordi Puig-Suari, Augustus S. Moore, Shinichi Nakasuka, "A New Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation", AIAA/USU Small Satellite Conference Proceedings V-5, 2000.

2. Robert J. Twiggs, Hank Herdt, Jordi Puig-Suari, "CubeSat Design Specification Document-Revision V", CalPoly & Stanford University, November, 2001.

3. Alan C. Tribble, "The Space Environment", Princeton University Press, 1995.

4. David K. Cheng, "Field and Wave Electromagnetics", Addison-Wesley, pp. 283-289, 1983

5. Willey J. Larson, James R. Wertz, "Space Mission Analysis and Design", Space Technology Library, pp. 416-424, 1992.

6. Freeman, R. L. 1981, "Telecommunication Transmission Handbook", John Wiley & Sons, 2nd Edition, 1981.

7. P. K. Mike Chepponis, "The KISS TNC: A simple host-to-TNC communication protocol", ARRL 6th Computer Networking Conference, January, 1987.

8. J. Hansen, "Using pic microcontrollers in amateur radio projects", QST, October, 1998.

9. The data sheets on PIC16F87x, Microchip Technology Inc.

10. The data sheets on MC13176, Motorola Inc.

11. The data sheets on MC13135, Motorola Inc.

12. The data sheets on FX-614, CML Inc.

13. "AX.25 Link Access Protocol for Amateur Packet Radio Ver. 2.2", TARP, 1997.