A Survey of CubeSat Communication Systems

(Draft)

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Abstract

This paper provides a short summary and compares the on-orbit performance of the communication subsystems on CubeSats in orbit today. Frequencies, modulations, antennas, and power outputs are discussed. COTS transceivers, modified and unmodified, and custom-built transceivers are compared and contrasted. Recommendations to new CubeSat projects about their communication subsystems are presented.

Contents

1 Introduction

This paper discusses the communications subsystems on CubeSats in orbit today, clearly showing that the communication system is one major limiting factor for CubeSats.

Chapter 2 discusses the common transceiver configurations, including just purchasing a COTS transceiver, purchasing then modifying a COTS transceiver, and custom-built transceivers. Chapter 3 goes into detail about each individual satellite's communications subsystem, including transceivers and antennas. Chapter 4 gives some recommendations to new CubeSat developers when building a communications subsystem.

1.1 CubeSat Standard

The CubeSat standard started as a joint project between Cal Poly State University and Stanford University in 1999[1]. Cal Poly Professor Dr. Jordi Puig-Suari and Stanford Professor Bob Twiggs imagined multiple 10 cm cubes in a jack-in-the-box type launcher after their experience building and deploying picosatellites from the Orbiting Picosatellite Automated Launcher(OPAL). Each picosatellite's mass is less than 1 kg, or the equivalent of a 10 cm cube of water[2].

While many criticize this standard as being "too small to do anything," universities and industry have shown that a lot of science and data collection is possible with these picosatellites. Novel new electronics, such as cheap cameras, processors, and sensors, gain space rating by flying in a CubeSat.

1.2 CubeSat Launches

Access to space constitutes the largest hurdle for universities building small satellites. While many large satellites launch from the US every year, the primary payload usually does not allow universities to attach anything to their rocket, uneasy that this addition might possibly harm the primary payload. The P-POD mitigates this fear by placing a strong protective box around the secondary payloads.

This accessibility problem, and because foreign launches are so much cheaper, forces most CubeSats to use foreign launch vehicles. To date, 17 CubeSats have flown on 4 foreign launch vehicles, and one CubeSat has flown on a US launch vehicle. Non-US launches present ITAR problems, and some universities have become entangled in this issue before clearing it up with the State Department.

2 Common Transceiver Configurations

Arguably, one of the most important parts of any satellite is the communications subsystem. Without any way to communicate with the satellite, the CubeSat would quickly become space junk. When selecting a communications subsystem for a CubeSat, three possibilities exist: buying a COTS transceiver, purchasing one designed for terrestrial use and modifying it, or building a transceiver from individual components.

2.1 COTS

Purchasing a COTS space-rated transceiver simplifies the design of the subsystem. Purchased transceivers typically accept standard serial data and perform all of the packetization, error checking, and retransmission. Most of the protocols and modulations are proprietary and device specific, requiring an identical radio at the command ground station.

Several companies build space-rated transceivers, but usually they are too expensive, heavy, and big for a CubeSat. The Stensat Group builds a transceiver specifically for CubeSats, with a 2m receiver and 70cm transmitter. Libertad-1 proved that the transmitter works in space[3].

2.2 Modified COTS

Designed for use on earth, many COTS transceivers would have serous problems functioning in space. A significant problem with commercial transceivers includes active thermal dissipation, as no air exists for convective cooling of the amplifiers. Required modifications for use in space include removing the case to reduce mass and size, drilling mounting holes, increasing transmit power, programming the transceiver to operate after power cycling, removing LCD displays and buttons, and changing the spread-spectrum timings to allow the radios to get a lock 3,000 km away. Some of these modifications require assistance from the manufacturer.

Microhard Systems builds a 2.4 GHz transceiver that has flown on several missions. However, it is extremely difficult to deal with and unsuitable for 1U CubeSats, requiring a very large dish to close the link. It also requires 1.1 watts of power just to receive[4, 5]. Other transceivers flown in space include the Alinco DJ-C4 and DJ-C5.

2.3 Custom-Built

Some projects, mainly universities, decide to build the entire transceivers out of individual components. Building a custom communications subsystem allows the next generation of students to learn about building small RF circuits. These transceivers have been less successful due to the inherent difficulties in RF board design.

Components of these custom-built transceivers include the terminal node controller (TNC), transceiver, and amplifier. Typically, the TNC consists of a microcontroller such as a Microchip PIC. Sometimes this same microcontroller also interfaces with the transceiver to program register settings during startup. Single-chip transceivers for the 433 MHz band perform well in the UHF amateur satellite band. Common manufacturers for such chips include Texas Instruments and RF Micro Devices.

2.4 Satellite Comparison

The table below shows a summary of the different communications subsystems of the satellites. Object number refers to the spacecraft ID number in the NORAD database. Amount Downloaded refers to the cumulative amount of data requested and downloaded by ground stations, not including protocol headers, forward error correction bits, or beacon data, as beacons transmit continuously.

Table 1: Summary of spacecraft transceivers.

Satellite	Object	Radio	Frequency	License	Power	TNC	Protocol	Baud Rate/Modulation	Amount Downloaded	Antenna
AAU1	27846	Wood & Douglas SX450	437.475 MHz	Amateur	500 mW	MX909	AX.25 on Mobitex	9600 Baud GMSK	1 kB[1]	dipole
CanX-1	27847	Melexis	437.880 MHz	Amateur	500 mW		Custom	1200 baud MSK	0[2]	crossed dipoles
Cute-1 (CO-55)	27844	Maki Denki (Beacon)	436.8375 MHz	Amateur	100 mW	PIC16LC73A	CW	50 WPM	N/A	monopole
		Alinco DJ-C4 (Data)	437.470 MHz	Amateur	350 mW	MX614	AX.25	1200 baud AFSK	?[3]	monopole
DTUsat-1	27842	RFMD RF2905	437.475 MHz	Amateur	400 mW		AX.25	2400 baud FSK	0[2]	canted turnstile
QuakeSat-1	27845	Tekk KS-960	436.675 MHz	Amateur	2 W	BayPac BP-96A	AX.25[4]	9600 baud FSK	423 MB	turnstile
XI-IV (CO-57)	27848	Nishi RF Lab (Beacon)	436.8475 MHz	Amateur	80 mW	PIC16C716	CW	50 WPM	N/A	dipole
		Nishi RF Lab (Data)	437.490 MHz	Amateur	1 W	PIC16C622	AX.25	1200 baud AFSK	?[3]	dipole
XI-V (CO-58)	28895	Nishi RF Lab (Beacon)	437.465 MHz	Amateur	80 mW	PIC16C716	CW	50 WPM	N/A	dipole
		Nishi RF Lab (Data)	437.345 MHz	Amateur	1 W	PIC16C622	AX.25	1200 baud AFSK	?[3]	dipole
NCube-2	28897[5]		437.505 MHz	Amateur			AX.25	1200 baud AFSK	0[2]	monopole
UWE-1	28892		437.505 MHz	Amateur	1 W	Integrated[6]	AX.25	1200/9600 baud AFSK	?[3]	dipole
Cute-1.7+APD	28941	Telemetry Beacon	437.385 MHz	Amateur	100 mW	H8S/2328[7]	CW	50 WPM	N/A	dipole
(CO-56)		Alinco DJ-C5	437.505 MHz	Amateur	300 mW	CMX589A	AX.25/SRLL	1200 AFSK/9600 GMSK	0	dipole
GeneSat-1	29655	Stensat (Beacon)	437.067 MHz	Amateur	500 mW		AX.25	1200 baud AFSK	N/A	monopole
		Microhard MHX-2400	2.4 GHz	ISM	1 W	Integrated[6]	Proprietary		500 kB	patch
CSTB1	31122	Commercial[8]	400.0375 MHz	Experimental	<1 W	Integrated[6]	Proprietary	1200 baud AFSK	6.77 MB[9]	dipole
AeroCube-2	31133	Commercial[8]	902-928 MHz	ISM	2 W	Integrated[6]	Proprietary	38.4 kbaud	500 kB[1]	patch
CP4	31132	TI CC1000	437.325 MHz	Amateur	1 W	PIC18LF6720	AX.25	1200 baud FSK	320 kB[1]	dipole
Libertad-1	31128	Stensat	437.405 MHz	Amateur	400 mW		AX.25	1200 baud AFSK	0[10]	monopole
CAPE1	31130	TI CC1020	435.245 MHz	Amateur	1 W	PIC16LF452	AX.25	9600 baud FSK	0[11]	dipole
CP3	31129	TI CC1000	436.845 MHz	Experimental	1 W	PIC18LF6720	AX.25	1200 baud FSK	1.6 MB[9]	dipole
MAST[12]	31126	Microhard MHX-2400	2.4 GHz	ISM	1 W	Intgrated[6]	Proprietary	15 kbps	>2 MB[1]	monopole

[1] Spacecraft worked on orbit but is now dead.
[2] Satellite never heard from in space.
[3] Japanese data downloaded is unknown as of 8 April 2008.
[4] Used a modified Pacsat protocol on top of AX.25. Source code available upon request.
[5] This object separated from SSETI Express months later and is presumed to be NCube-2.
[6] The radio module accepts serial data and uses an internal TNC.
[7] This is the main satellite processor.
[8] The exact model number is unknown.
[9] As of 8 April 2008.
[10] No uplink commands received by spacecraft.
[11] The CAPE1 team knew the receiver was dead before integration but had no time to fix it.
[12] One identical radio per satellite section.

3 Satellite Details

3.1 Eurockot Launch

Coordinated by the Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies, this rocket launched from Plesetsk, Russia, on 30 June 2003, in a polar sun-synchronous orbit. Three different deployment systems were used on this flight, including two Mark I P-PODs from Cal Poly, a Separation Mechanism built by Tokyo Institute of Technology (Tokyo Tech) for CUTE-1, and a T-POD built by the University of Tokyo for XI-IV. Integration occurred at the University of Toronto.

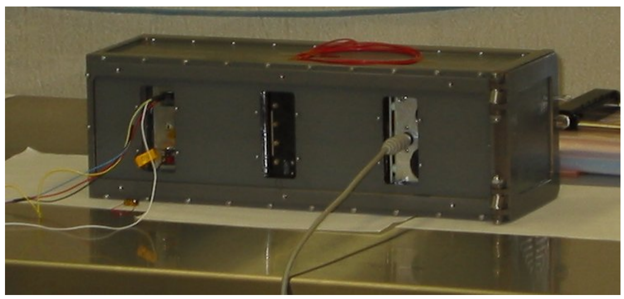

Figure 1: The P-POD with AAU1 Cubesat, DTUsat-1, and CanX-1.

3.1.1 AAU1 CubeSat

The first satellite built by Aalborg University of Denmark, AAU1 CubeSat's goal included teaching students about satellites and giving them hands on experience with pico-satellite technology. AAU1 CubeSat included a camera and other various sensors. Radio amateurs could barely receive the beacon, and only limited amounts of data has been downlinked[6].

The satellite's communications subsystem used a center loaded dipole antenna to transmit and receive. The transmitter operates at 500 mW with GMSK encoding in half-duplex mode. Onboard forward error correction increased the link reliability but decreased data throughput. The system uses a 9600 baud rate for communications.

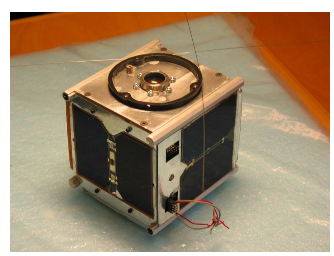

Figure 2: AAU flight model.

Using a MX-COM MX909 TNC chip, this satellite used a Mobitex packet encoding scheme underneath standard AX.25. These packets contained telemetry data, but could not be decoded by regular amateur radio operators due to the Mobitex packet encoding[7].

This satellite beacons every two minutes if the on-board computer does not function, and every four minutes in a low battery situation. Ground stations reported hearing AAU1 CubeSat shortly after launch, but downlinks ceased after about 3 months due to battery problems. The team theorizes that a short circuit in the antenna reduced the radiated energy. Ground stations only received about 1 kB of data[8].

3.1.2 DTUsat-1

Students from the Technical University of Denmark built DTUsat-1, with a primary purpose of education. The primary payload consisted of testing a new and innovative tether deployment system with a 450 meter electrodynamic tether. The design of the electronics will force the satellite to slowly deorbit. The secondary payload included a calibrated test transmitter and camera, neither of which flew[9].

The communications subsystem of this satellite included a custom made transceiver built around a RF Micro Devices RF2905, a all-in-one transceiver chip designed for ISM devices. The data rate is 2400 baud. The RF output of the satellite is 400 mW at 437 MHz[10].

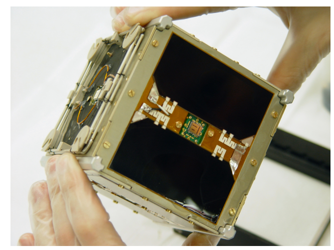

Figure 3: DTUsat-1 in the clean room before integration[9].

Instead of the standard tape-measure antenna, this satellite used solid 2 mm rods of aluminum. A square route consumed one whole side, with no room for solar panels. To allow a full quarter wave antenna, springs along the length of the antenna allowed the rods to bend at the corners of the route. The pattern resembles a canted turnstile. The antenna released by a nichrome wire melting a string holding the antenna in place[9].

Due to perceived import regulations, the team brought DTUsat-1 into Canada for integration in multiple pieces. After assembling the satellite and performing minor testing, students integrated it into the P-POD.

The operations team never heard DTUsat-1 in space. After thorough testing of the engineering unit, the team does not know the origin of the problem. The flight spare hardware still works. Multiple ground stations across Europe helped with trying to find the satellite in the days and weeks after the launch. The ground station at DTU consisted of two phased yagis connected to a Yaesu FT-847.

3.1.3 CanX-1

This first CubeSat from University of Toronto's Institute For Aerospace Studies contained several payloads. Two Agilent cameras, one black-and-white and one color, were supposed to take pictures of the stars and horizon for attitude determination. Active magnetorquers allowed the spacecraft to aim the cameras. The plan also included COTS GPS receiver for location, and an ARM9 microprocessor for controlling the satellite[11].

As with many CubeSats today, this satellite used a single transceiver in the UHF amateur satellite band[12]. A Melexis chip, designed for remote keyless entry, formed the heart of the radio, and a power amplifier allowed 500 mW of output power. CanX-1 used a custom protocol on top of 1200 baud MSK. While this may have allowed for a stronger link, it makes building a ground station a lot harder due to the custom parts required, and the inability to use a backup ground station if the primary fails[13].

Due to time constraints, a mass model was integrated into the P-POD during integration at the University of Toronto. Vibration tests occurred with the mass model. In Russia, teams deintegrated the CanX-1 mass model and replaced it with the finished satellite. After they finished the satellite, the team focused their energy on building the ground station.

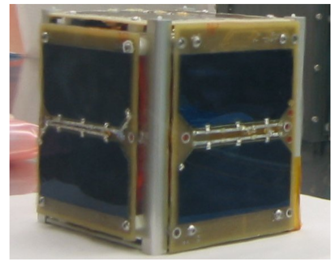

Figure 4: CanX-1.

CanX-1 never functioned on orbit. No signals were ever received, so there are few theories about what went wrong. The team spent time at the Algonquin Radio Observatory in Ontario, Canada, listening for the local oscillator, but heard nothing, suggesting that a power problem killed the satellite[13].

3.1.4 Cute-1

The first CubeSat from Tokyo Tech, CUbical Titech Engineering Satellite (CUTE-1) performed three missions, including a sensor experiment, deployment test, and a communications experiment[14]. The communications experiment consisted of changing the modulation schemes between standard AX.25 and SRLL, a new protocol developed for the project. SRLL includes error correction and can correct for up to 3 erroneous bits per 32 byte packet[15].

The communications subsystem included a 2 m receiver, a 1200 baud FM transmitter at 437 MHz, and a CW transmitter at 437 MHz. Each radio connects to an associated monopole antenna. A single antenna route with a nichrome heater and nylon wire cut the antennas free once in orbit. The CW beacon uses a simple PIC16 to generate the tones, then uses a custom Maki Denki transmitter chip at 437 MHz with an output of 100 mW. It operates almost continuously, making it really easy to track this satellite[16].

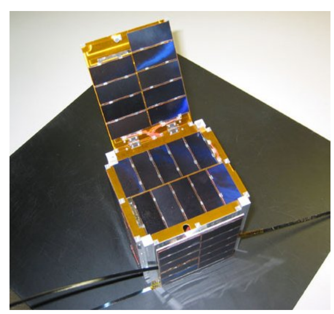

Figure 5: Cute-1 flight model.

The 2 meter command uplink receiver consists of an Alinco DJ-C1, a single band “credit-card” style transceiver. DTMF modulation is used for the uplink commands. The downlink transmitter consists of an Alinco DJ-C4, identical to the uplink receiver except for the 70 cm band. Nominal output is 350 mW, and must be turned on by the Tokyo Tech control station. Once on, the downlink transmitter sends AX.25 or SRLL data until the buffer runs out, or approximately 40 minutes[16].

3.1.5 QuakeSat-1

Stanford University and QuakeFinder collaborated on this 3U CubeSat designed to measure signal amplitudes in the VLF range. This satellite used a downclocked Diamond Systems Prometheus PC-104 CPU for the main processor running a slightly modified Red Hat 9 operating system. Due to the four deployable solar panels, the satellite always had plenty of power.

The 436 MHz transceiver on this satellite consisted of a Tekk KS-960, a crystal-controlled data radio. This radio was slightly modified by replacing all of the electrolytic capacitors with tantalum and adding conductive foam around the power amplifier to prevent the amplifier from overheating. It produces 2 watts of RF power and is 23% efficient. This satellite used a Tigertronics BayPac BP-96A hardware TNC[17].

This satellite also used a cheap DTMF decoder chip attached to the radio as a satellite hard reset. This easy to use feature only requires a DTMF code to reset and power cycle the satellite, with the audio for the circuit tapped off the main receiver. Stanford used this several times to rescue the satellite from a locked state[18].

When on, this satellite beaconed a short 200 byte packet every 10 seconds, making it a really easy to find and a good 9600 baud source in space. The downlink protocol uses a derivative of the Pacsat protocol, especially well suited for satellite communications because it is NACK based and easily decoded by many amateur tracking stations around the world. Due to battery failure about 7 months after launch, this satellite turns off for eclipse and must be manually controlled back on, making this source less reliable now.

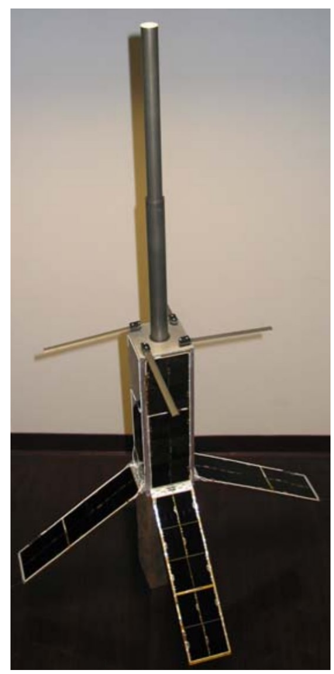

Figure 6: QuakeSat-1 on display[19].

While this paper does not intend to describe any of the payloads aboard these satellites, this payload is a communications experiment. The magnetometer could measure the VLF band with four different filter bandwidths and sampling profiles. Mode 1 measured from 0.5 to 10 Hz at 50 samples/sec, Mode 2 measured 10 to 150 Hz at 500 samples/sec, Mode 3 measured 10 to 1000 Hz at 3000 samples/sec, and Mode 4 measured the 140 Hz passband from 127 to 153 Hz at 500 samples/sec. These different modes allowed the researchers to store varying amounts of data as the satellite passed over regions around the world in the aftermath of a strong earthquake. The sensitivity of the magnetometer is 10 pT. The VLF receiver experiment returned inconclusive results[19].

QuakeSat-1 also used two ground stations linked via the internet to download more data[20]. Each ground station consisted of an Icom 910 transceiver, VHF and UHF yagi antennas, a commercial rotor, and a TNC, all completely accessible via the internet. The first ground station, located at Stanford, started a data downlink session, and the other ground station in Alaska continued receiving the data after the satellite went below the horizon at Stanford. This configuration allowed 423 MB of data downloaded from this triple CubeSat, the most from any CubeSat in space as of April 2008[18].

3.1.6 XI-IV

This 1U CubeSat from the Intelligent Space Systems Laboratory at the University of Tokyo is the first in the XI (sai) series to fly in space. The first three "satellites" were built as bench models. The mission of this spacecraft included student education and verification of a working satellite bus for future missions. The payload consisted of a small cellphone-type camera.

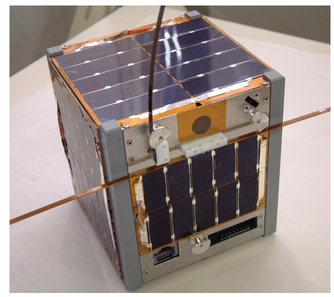

Figure 7: XI-IV in the clean-room.

The entirely custom made communications subsystem included one uplink receiver, one beacon transmitter, and one telemetry transmitter. The TNCs consisted of various different PIC16 microcontrollers, and the transmitters and receivers comprise of custom chips from Nishi RF Lab with 1 watt of output power[21].

Much like Cute-1 (Section 3.1.4), the CW beacon operates almost continuously. 6 different CW messages rotate through all pertinent telemetry data, including on-board computer status, temperatures, voltages, and currents[22]. The almost continuous beacon makes it a very good reference for testing ground station performance, and also makes it very easy to track the satellite.

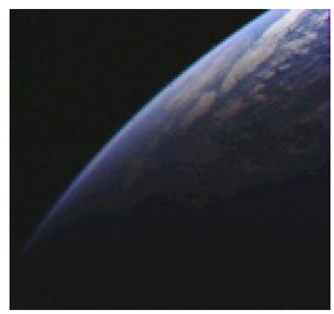

Figure 8: Earth picture taken by XI-IV.

The ground station at the University of Tokyo consists of an Icom 910D and various TASCO TNCs. The antennas, manufactured by Creative Design, consist of two phased yagis on 2 m and two phased yagis on 70 cm[23].

Since the University of Tokyo is more interested in operating their newer XI-V satellite, they have graciously let ordinary amateur satellite operators in Japan, and students at Cal Poly State University, command the satellite and take pictures. An on-line schedule permits amateurs to take pictures and store them in memory for download later.

While some of the picture storage memory on the satellite does not work anymore, the rest of the satellite operates beautifully to this day. Students at the University of Tokyo, Cal Poly, and Luleå Institute of Technology in Kiruna, Sweden, participated in several handoff experiments to see how much more data could be downloaded from a ground station network[24, 25].

3.2 SSETI Express Launch

A Cosmos-3M launch vehicle from Plesetsk, Russia, on 27 October 2005 placed SSETI Express (XO-53) in a polar orbit at 700 km. This microsatellite, just over 50 kg, also carried 3 CubeSats inside. Sponsored by the ESA Education Department, this satellite brought together many universities across Europe, educated many students, and caught the attention of many members of the public.

SSETI Express failed almost immediately after launch. One transistor, designed to keep the batteries from overcharging, failed shortly after launch, shorting the solar panels to ground. The satellite operated on batteries for a few days. The T-PODs deployed their satellites 1.5 hours after launch. XI-V and UWE-1 deployed successfully, but radar observations showed that NCube-2 did not deploy[26].

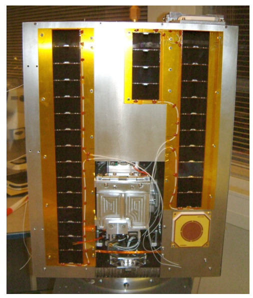

Figure 9: SSETI Express during construction. The T-POD door is visible in the center of the picture.

3.2.1 XI-V

XI-V began life as an engineering model of XI-IV. Consequently, it contains the exact same electronics and payload as XI-IV, and operates exactly the same[21]. The only differences consist of different solar cells for space testing and new software. This satellite still functions normally, but slight intermittent problems with the camera exist.

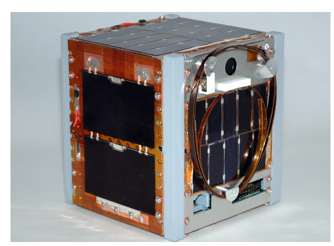

Figure 10: XI-V.

The hardware of the communications subsystem exactly replicates the XI-IV satellite. However the satellite builders added their own comments, up to 25 characters, as another section in the CW beacon. Students chose serious topics, such as `SPACE-THE.FINAL.FRONTIER.`, and others chose funny ones such as `DAWNOFTHEREALSPACEAGE.YN-`.

As with its sister satellite, XI-V still functions normally today. Students at the University of Tokyo still download pictures regularly, and the beacon still works.

3.2.2 NCube-2

NCube-2 was a CubeSat developed by students from several universities in Norway and was coordinated by Andøya Rocket Range and the Norwegian Space Centre. The satellite's payloads included an Automatic Identification System(AIS) and attitude determination and control. NCube-2 was launched on SSETI Express, but it is unclear if NCube-2 was ever ejected from SSETI. During integration and testing, NCube-2's gravity boom prematurely deployed into SSETI Express several times[27].

NCube-2's uplink and downlink operated on two different frequencies bands. Command receive was located on 145MHz and downlink operated on 435 MHz. For the receive frequencies, a dipole antenna was used while a quarter wave monopole antenna was used for transmitting[28]. The original design of NCube-2 used a L-Band transmitter for downlink and GPS receiver, but these experiments were not implemented.

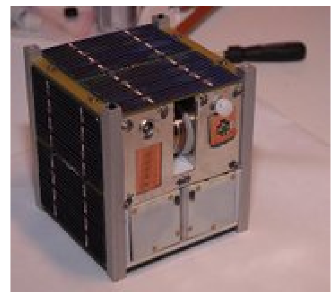

Figure 11: NCube-2.

Since NCube-2's mission includes receiving and retransmitting AIS signals, NCube-2 needed hardware compatible with the AIS system. Although AIS transmits on both 161.975 MHz and 162.025 MHz, the NCube-2 team decided to simplify their design and only use one of the frequencies. The TNC chosen for the task of decoding the AIS signals was the MX589TN high speed GMSK modem. No signals were ever heard from NCube-2[29].

3.2.3 UWE-1

This satellite, from the University of Wurzburg in Germany, was designed to test TCP/IP protocols in space, and the effects of low bandwidth, long path delays, and dropped packets[30]. The university had an internet-to-satellite gateway that allowed any users on the internet to access the satellite much like a networked hard drive.

The main processor included a Hitatchi H8S-2674R microprocessor running µCLinux[31]. Magnetic torquers allowed spacecraft stabilization on two axes, with the antenna as a gravity gradient on the other axis.

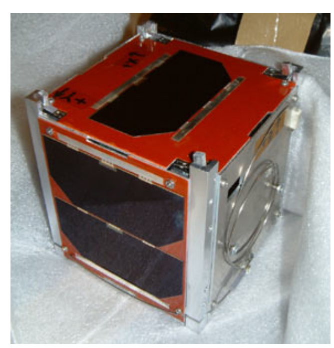

Figure 12: UWE-1.

This satellite beaconed every one minute with a short 1200 baud AFSK packet. The university ground station had troubles receiving the satellite in the first few days after launch due to faulty equipment and weather. Luckily, numerous other ground stations around the world received these beacons and forwarded the data on to the university[32]. This data showed that the satellite was stable and working fine. Within a week, the university fixed the ground station, and normal operations ensued. UWE-1 stopped functioning in November 2005, about 3 weeks after launch.

3.3 M-V-8 Launch

This rocket, sponsored by JAXA, performed the first launch of a CubeSat from the Kagoshima Space Center in Japan on 22 February 2006. Placed in a 700 x 300 km elliptical polar orbit, the satellite is expected to deorbit within a few years of launch[33].

Figure 13: M-V-8 launch with Cute-1.7+APD. Photo courtesy of JAXA.

3.3.1 CUTE-1.7+APD

CUTE-1.7+APD, built by Tokyo Tech University, completely redesigned the Cute-1 bus around common consumer electronics. A common PDA, running Windows CE 4.1 with the display and case removed, formed the main computer. The main computer addressed external devices, such as the radios and data acquisition module, through a common USB hub[34].

The main payload constituted of an avalanche photo detector to measure particles in the atmosphere. A secondary payload incorporated an attitude control experiment, with gyroscopes, magnetometers, and camera controlling three orthogonal magnetorquers. Another payload included an active deorbit tether. While this is a 2U CubeSat, it does not have standard rails. Students designed a custom deployer for this satellite, and the deployer used a nichrome heater to separate within 5 seconds.

Figure 14: Cute 1.7+APD.

This satellite contained two receivers and two transmitters. The command uplink receiver listened in the VHF amateur radio band, and the store-and-forward message box listened at 1200 MHz. Both the CW beacon and data downlink transmitters reside in the UHF amateur band. The data downlink transmitter can switch between 1200 baud AFSK packet and 9600 baud GMSK packet depending on the satellite mode. The L-band uplink allows for the satellite to operate as a store-and-forward packet satellite, open to the public. This satellite allows Simple Radio Link Layer packets as well as AX.25[35].

This satellite stopped functioning in the beginning of May 2006, transmitting an unmodulated carrier on the UHF data frequency. This condition will likely continue until the batteries fail.

3.4 Dnepr 1 Launch

Cal Poly's first launch campaign began in late 2004. This launch contained no "primary," just a collection of smaller secondary satellites. Most of the 23 satellites (including the 14 CubeSats) contained some sort of educational mission, so students worked on every satellite in this cluster launch except one.

This launch failed on 26 July 2006, devastating the CubeSat community. 14 CubeSats ended up in terrasynchronous orbit after the rocket motor turned off after 73 seconds. The satellites crashed into the steppes of Kazakhstan, leaving a 50 meter crater outside the accepted crash zone[36, 37].

3.5 Minotaur Launch

The first US launch of a CubeSat, this rocket went up on 11 December 2006. The primary payload of this rocket included TacSat-1, an Air Force communications satellite. The rocket went to a 40 degree inclination, and dropped GeneSat-1 off on the way at approximately 410 km. Strapped to the side of the upper stage motor casing, this P-POD fired backwards after the motor turned off.

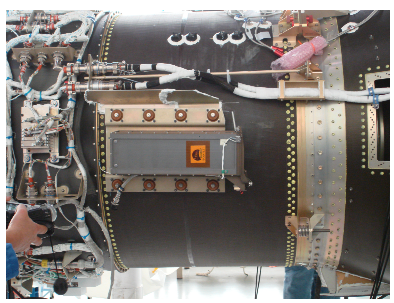

Figure 15: The P-POD, with GeneSat-1 inside, strapped to the side of the Minotaur Launch Vehicle upper stage motor casing. The third stage at right will fall away before the satellite ejects.

3.5.1 GeneSat-1

NASA Ames Research Center Astrobionics group, Santa Clara University, and Stanford University collaborated on GeneSat-1, a 3U CubeSat designed to study the biological effects of radiation in low earth orbit. Other objectives include education and outreach through the UHF beacon, developing a standard bus for biological experiments, and investigating small satellites as a proving ground for novel technologies[38].

The entire GeneSat-1 bus consumed 1U of this satellite. As part of the educational outreach objective, this satellite contained a beacon. Not originally included in the spacecraft's design, the beacon resided on the end of the satellite. The payload consisted of a sealed pressurized vessel containing optical sensors and fluids for bacterial growth.

This satellite used a commercial-off-the-shelf Microhard MHX-2400 2.4 GHz spread spectrum radio for the payload data downlink. Maximum output power is 1 watt with an overall efficiency of 22%. This radio uses a proprietary packet format with GFSK on top of frequency hopping spread spectrum.

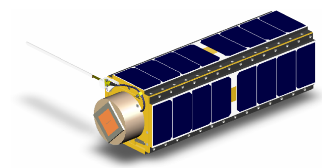

Figure 16: GeneSat-1 showing the 2.4 GHz patch antenna and UHF beacon assembly on the end[4].

In order to communicate with the satellite at 10 degrees, the link budget required a 60 foot dish for a 10 dB margin. The project used SRI International's dish at Stanford University. The dish needed several modifications before it could be used at 2.4 GHz, including the installation of new mesh and construction of a weatherproof case to house the Microhard radio up at the feedpoint. The GeneSat-1 team downloaded about 500 kB of telemetry over the Microhard radio[4].

The GeneSat project also sponsored an Amateur Radio contest. Who ever listened to the most beacons during the experiment phase could donate a complete earth station to any university of their choosing. Ralph Wallio, W0RPK, of Iowa won the contest with the most beacons heard.

3.6 Dnepr 2 Launch

The Dnepr 2 launch blasted off from Baikonur Cosmodrome in Kazakhstan on 17 April 2007. Unlike the first Dnepr launch, this one successfully deployed 3 P-PODs in space, dropping the satellites in a polar orbit between 650 and 770 km.

Integration occurred during the middle of March 2007. Integration went smoothly, but a problem with an upper stage connector arose during final testing of the rocket. Instead of trying to find and fix the problem, Kosmotras decided to just switch the rocket with a new one. After reintegration of the Space Head Module onto the new rocket, it blasted off at 06:46 UTC.

Figure 17: The first P-POD with MAST inside mounted to the Space Head Module.

3.6.1 CSTB1

This 1U CubeSat, from The Boeing Corporation, contained a camera and a magnetometer for measuring attitude. It also contained a deorbit mechanism to increase the drag and deorbit the spacecraft within the specified 25 year requirement. The camera has taken over 50 pictures of the earth.

CSTB1 used two commercial transceivers for the communications subsystem. A custom antenna switch allowed both transceivers to use the same antenna. Modifications to the transceivers included removing the cases, adding thermal paste to conduct heat away from the amplifiers, and removing the screen and buttons. Two PIC microcontrollers worked as redundant TNCs.

This satellite, operating at 1200 baud, currently has downloaded 6.77 MB of picture and telemetry data. It still works well. The deorbit mechanism has deployed and is functioning nominally[39].

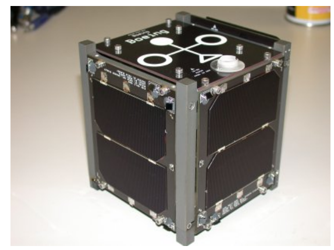

Figure 18: CSTB1. Photo reprinted with permission of The Boeing Corporation.

3.6.2 AeroCube-2

The Aerospace Corporation of El Segundo, CA, built AeroCube-2 as the next iteration to their AeroCube-1 satellite which was lost in the Dnepr 1 crash. The payload contained a small camera for taking pictures immediately after ejection from the P-POD, and took the famous picture of CP4 in space (see Figure 20).

The communications subsystem of this satellite comprised of a commercial spread-spectrum 900 MHz radio modified to work in space. Those modifications included increasing the transmit power to 2 watts, increasing receiver bandwidth to account for doppler shift, and changing the frequency hopping timings for large distances. The baud rate of the radio is 38.4 kbaud, and the downlink record for a single pass is 384 kB[40].

When commanded, the satellite transmits through an omnidirectional patch antenna to the 60 foot dish at SRI International in Menlo Park, CA. This ground station has downloaded approximately 500 kB of picture data in total. This figure would be higher if the battery charging circuit worked; the satellite died prematurely from dead batteries[40].

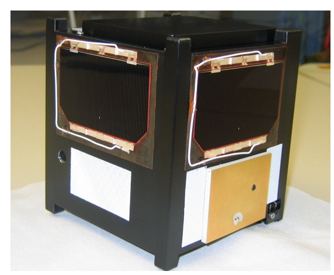

Figure 19: AeroCube-2 before integration. Photo reprinted with permission of The Aerospace Corporation.

3.6.3 CP4

This satellite from Cal Poly State University demonstrated the first version of the CPX bus. The CP2 team took all the lessons learned from Cal Poly's first satellite, CP1, and applied them to this satellite. Due to Russian launch manifest inflexibility, the CP2 satellite flew with the CP4 name because the manifest required a satellite named "CP4" in the P-POD, and a satellite name change was easier than changing the manifest.

This satellite used an 8-bit PIC18LF6720 as the C&DH microcontroller. The clock speed is 4 MHz, and a single I^2C bus snakes all over the satellite, with an I^2C MUX device for device failure isolation and bus address conflict resolution[41, 42]. 128kB of redundant external memory, addressed over the I^2C bus, augments the 128k of memory inside the PIC microcontroller. Power comes from dual-junction solar panels on five sides of the satellite[43].

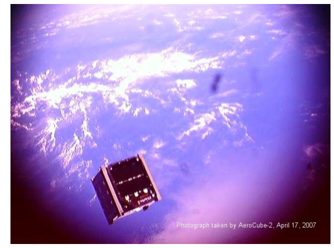

Figure 20: CP4 in space. This picture was taken by AeroCube-2 (Section 3.6.2) a few minutes after ejection from the P-POD.

The communications subsystems contains two identical radios. Each radio contains a PIC processor, a Chipcon CC1000 single chip transceiver programmed for 437 MHz, and a RF2117 one watt amplifier. The PIC processor for each radio converts the data from the C&DH into a standard 1200 baud AX.25 frame, programs the CC1000 with the correct frequency and power output, and regulates the start-up sequence of the RF2117 amplifier chip[44, 45].

Immediately after launch, the CP4 operations team noticed the satellite had very poor receive sensitivity. The very loud autonomous beacon verified that the transmitter worked fine, but only above elevations of 30 degrees would the satellite respond to commands. Also, it appears that long commands sent to the payload do not work most of the time, possibly due to bit flips in the transmissions up to the satellite.

One of the ground stations at Cal Poly consists of a Yaesu FT-847, a 100 watt linear amplifier, and two phased high-gain yagi antennas. The other station consists of an Icom 910H radio with 2 m and 70 cm yagis. Both fully independent stations use software TNCs and Yaesu G-5500 rotors. The total data downloaded from CP4 is approximately 320 kB.

CP4 partially failed in orbit after about 2 months during a large data download. The communications subsystem microcontrollers are alive and respond to a limited set of commands, but the main C&DH microcontroller does not respond at all. Every few days the operations team contacts CP4 and commands it to beacon, but no valuable data exists in the beacon. While the exact cause will never be known, the team theorizes that a device on the I^2C bus failed, causing all internal communications to cease. The I^2C bus on the satellite always had problems, mostly caused by very high board capacitance. CP3 corrected most of those problems but still has poor receive sensitivity.

3.6.4 Libertad-1

Universidad Sergio Arboleda, a private university located in Bogota, built this first Colombian satellite. The primary mission of this satellite included starting a satellite program in Colombia to build expertise and knowledge in the field of satellite engineering[46]. Libertad-1, the first in the "Colombia en órbita" project, generated lots of interest and excitement across the country. It motivated lots of other people to consider engineering as a future career path.

This satellite used a structure and main processor from a Pumpkin Kit. While original payload plans included a GPS and camera, time and budget constraints prevented the completion of the payload. Students designed and built their own custom power board and side panels. However, due to ITAR complications, the satellite flew with no solar cells attached. Two secondary cells, one for the satellite and one for antenna deployment, provided the only power for the satellite after launch. The batteries lasted for about 34 days, after which the satellite went silent[47].

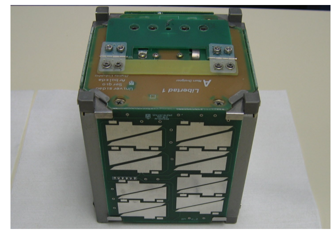

Figure 21: Libertad-1 during integration into the P-POD.

A standard Stensat radio formed the heart of the communications subsystem, with uplink on 2 meters and downlink on 70 cm. The beacon consisted of a five AX.25 packets every 10 minutes, with internal side panel and microcontroller temperatures as the only telemetry[3]. This long period frustrated listeners, as an entire pass could happen with no beacons heard. The primary ground station at the university did not work during the launch campaign, and due to a failed rotor just after launch, no uplink attempts were made.

3.6.5 CAPE1

The Cajun Advanced Picosatellite Experiment satellite (CAPE1), built by the University of Louisiana at Lafayette, contained a PIC18LF6722 for the main processor. The purpose was to flight test the CAPE bus and receive diagnostic data.

CAPE1 used a CC1020 single-chip transceiver at 435 MHz with a RF2117 one watt amplifier. The satellite used a PIC16LF452 for the 9600 baud TNC[48]. The antenna, originally a turnstile with the tape-measure elements protruding from the sides, was downgraded to a standard dipole because the turnstile lacked a good ground plane.

Figure 22: CAPE1. The turnstile antenna doors are visible above the solar cells.

This satellite transmitted two beacons, a 30 second CW preamble followed by a short 9600 baud packet bust, repeating once per minute. Nobody has ever decoded a 9600 baud packet, including the CAPE1 ground station, leading the team to surmise that there was some problem with the packet format. Luckily, most of the data contained in the packet also existed in the CW portion of the beacon, so the loss of the packet did not affect the satellite health knowledge. Amateur radio operators listening to the VHF downlink of VO-52 heard CAPE1's beacon through the transponder on numerous occasions.

Lack of development time prevented the receiver from functioning according to the specification. With no time to fix this problem, the satellite flew with a very deaf receiver.

This satellite died 4 months after launch, but recently revived itself in March 2008. It beacons intermittently[49].

3.6.6 CP3

CP3 continues with the same bus as CP4 (section 3.6.3). Minor incremental updates include higher capacity batteries, more efficient solar panels, a new battery protection circuit, different payload, and removal of wire mods. The payload consisted of two imagers for taking pictures of the earth. A total of 1.6 MB of data has been downloaded from CP3 as of 8 April 2008.

CP3 also suffers from poor receive sensitivity, as it is an exact replica of the CP4 communications subsystem except at 436 MHz. Several possibilities exist to remedy this situation for the next launch, including adding a low noise amplifier before the receiver, mitigating internal spacecraft noise with shielding, and lengthening the antenna to a full half-wave dipole.

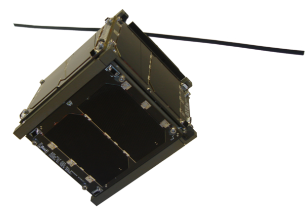

Figure 23: CP3.

This satellite still functions in orbit, but for some unknown reason goes silent for many weeks at a time. When it does come back alive, the satellite operates normally and no resets occurred during its away time. Possible theories for this disappearance include the satellite rotating into severe antenna nulls due to an unknown permanent magnet on the satellite. Spinning up the satellite with the magnetorquers may help, but the torquing must occur on one axis only, as the on-board implementation of B-dot will not work because of one mislabeled variable in the C&DH code.

3.6.7 MAST

The Multi-Application Survivable Tether experiment, built by TUI, looked at micrometeorite impacts on space tethers. This 3U satellite contained three sections: the tether deployment unit "Ted," the tether inspector satellite "Gadget," and an endmass "Ralph." Each section could be considered an entire spacecraft, as each contained a space-rated GPS receiver, CPU, power system, and transceiver[50].

Ideally, a few days after launch the tether deployment unit would deploy 1 km of tether. The tether inspector unit would take pictures of the tether, and downlink the pictures for ground analysis. The proprietary Hoytether allows several strands to break before failure. In reality, the tether did not fully deploy due to very low separation velocity. Radar measurements show the tether deployed just 1 meter.

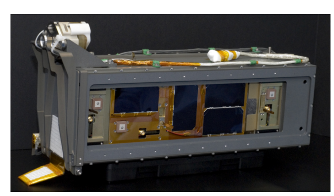

Figure 24: MAST inside a P-POD[5].

The communications subsystem aboard each of the three sections were comprised of a 2.4 GHz Microhard MHX-2400 transceiver[5]. The satellites did not talk amongst themselves, but only directly with the ground station. Due to a very slim link margin, less than 10 dB, this project used the 60 foot dish at SRI International. At the ground station, an identical flight radio placed at the dish feedpoint communicated via standard serial to computers in the radio room. These computers connected to the internet, allowing unattended operation except the dish operator.

Communication issues prevented these satellites from completing their mission. The Aerospace Corporation booked the SRI dish, so no communication attempts with MAST occurred for the first three days. During these three days, the satellites receivers were on continuously, draining the batteries to critical states. When only receiving, the Microhard consumes around 1.1 watts of power. This may be acceptable for a triple cube, but a single cube will have trouble generating this amount of power[51].

With the batteries discharged, the main processor forced the receivers to turn off, except for certain portions of the orbit. This required on-board orbit propagation. Switching on and off the receivers allowed the batteries to recharge, but the link suffered tremendously. Only the tether inspector satellite successfully communicated with earth, downloading more than 2 MB of data. It died three weeks after launch[5].

4 Communications Subsystem Recommendations

While writing this paper, several recommendations to new satellite developers became obvious:

- Include a long beacon. All of the Japanese CubeSats are so easy to track because they contain CW beacons that operate almost continuously. While the beacons are very low power, on the order of 100 mW, they are easily received by a common SSB receiver and an omnidirectional whip antenna. Include as much spacecraft data on this beacon so that you can learn about your satellite even if uplink does not work.

- Use "common" amateur modes for data communication. After the CP4 launch, several radio amateurs around the world tracked our spacecraft on every pass. These amateurs, including Mike Rupprecht in Germany and Colin Hurst in Australia, forwarded all packets to our ground station, increasing our knowledge of our satellite tremendously. Colin Hurst even wrote up a complete attitude determination paper for CP4[52].

  However, there are downsides to using common modes. The common 1200 baud data rate is just too slow for large amounts of data, and there is no forward error correction or compression in the AX.25 protocol. The CubeSat community needs to coalesce around a new "common" mode, one that emphasizes data rate and error correction.

- Include a simple reset in case the satellite becomes non-responsive. QuakeSat-1 ground operators used a simple DTMF code several times to rescue the locked-up satellite. If CP4 contained a command to fully reset the satellite, maybe we could reset the processor and it would start functioning normally again.

- Verify your ground station early. Several universities launched satellites without functioning ground stations. There is no reason to launch a satellite if you can't communicate with it! Test your ground station by talking to other amateur radio operators through a satellite. Listening to beacons lets you test the ground station receiver, but does not verify the transmitter. A great opportunity for CubeSat developers at universities to network occurs on College Night on AO-51, twice a month on Thursday during the evening passes.

- Don't depend on another ground station to close your communications link. MAST operators couldn't talk with their satellite for three days because another satellite booked the dish they needed, and this lack of communication probably caused the mission to fail. Each organization building CubeSats should have full unrestricted access to a local ground station, usually situated in the same building as the satellite development lab.

- Get an AMSAT mentor. If your project intends to use amateur radio frequencies, mentors are invaluable resources when trying to learn about the amateur radio service. Most mentors know a lot about electronics and RF systems. The can tell you exactly how to build a ground station, and will usually allow their station as a back-up in case the primary ground station fails during operations. Mentors can be found by contacting local AMSAT groups directly.

5 Conclusion

A quick look at Table 1 shows that the amount of data downloaded from CubeSats in orbit right now is very small. Excluding QuakeSat-1 and the Japanese CubeSats, the total data downloaded is 11.69 MB for 13 satellites over 5 years. This is a very small number, highlighting the need for a good transceiver capable of fitting within the CubeSat form factor and weight/power constraints.

An ideal radio designed for CubeSats does not exist at this time. However, there are several transceivers that have successfully flown in space and returned large amounts of data to earth. Most of those radios are commercially available. The CubeSat community also needs to settle on a new "standard" modulation scheme, with larger data throughput. This standard modulation scheme will allow universities to track each others spacecraft and forward data.

Some groups are trying to combat this data deficiency by networking many ground stations, similar to the ground station in Alaska for QuakeSat-1 but over a much larger scale. The Global Educational Network for Satellite Operators (GENSO) project aims to link hundreds of low cost amateur radio ground stations via the internet[53]. It will also allow remote control of satellites from ground stations around the world, greatly increasing satellite health knowledge. GENSO is scheduled to be open to any interested parties in Summer 2009.

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