A Survey of CubeSat Communication Systems

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Abstract

This paper provides a short summary of the communication subsystems on CubeSats in orbit today, and compares their on-orbit performance. Frequencies, modulations, antennas, and power outputs are discussed. COTS transceivers, modified and unmodified, and custom-built transceivers are compared and contrasted. Recommendations for the communication subsystems of new CubeSat projects 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 1 provides background information on the CubeSat project and describes how the amateur radio and CubeSat communities work together. Chapter 2 discusses the common transceiver configurations, including 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 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 10cm cubes in a jack-in-the-box type launcher after their experience building and deploying picosatellites from the Orbiting Picosatellite Automated Launcher(OPAL), a 23 kg nanosatellite. Each picosatellite's mass is less than 1 kg, or the equivalent of a 10cm 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 ratings by flying in a CubeSat.

1.2 CubeSat Launches

Access to space constitutes the largest hurdle for universities building small satellites. While many satellites launch every year, the primary payload usually does not allow universities to attach anything to their rocket, concerned that this addition might possibly harm the primary payload. The Poly Picosatellite Orbital Deployer (P-POD) mitigates this fear by placing a strong protective box around the secondary payloads and thoroughly testing satellites for structural strength. Variants of the P-POD include the University of Toronto's X-POD and by the University of Tokyo's T-POD, both of which have flown.

This accessibility problem, and the fact that foreign launches are so much cheaper, forces most CubeSats to use foreign launch vehicles. To date, 23 CubeSats have flown on 5 foreign launch vehicles, and one CubeSat has flown on a US launch vehicle. Non-US launches present an ITAR problem, and some universities have become entangled in this issue before clearing it up with the State Department.

1.3 Amateur Radio Involvement

To a few in the amateur radio community, all of these CubeSats just steal frequencies and don't benefit the community at all. However, most of the teams provide clear benefits to the amateur radio community, including more licensed hams, new modulation schemes and modes, increased awareness of the issues challenging amateur radio today, international collaboration, and education of a new generation of amateur radio operators. These new hams are the future of the amateur radio hobby, and will steer the hobby in new directions while fighting against new threats to the hobby[3].

At Cal Poly State University, students are encouraged to obtain their amateur radio license so they can track satellites without a control operator. Approximately 70% of the students working on the CubeSat project acquired their amateur radio license while on the project, and many use their license for terrestrial communications.

It seems that countries outside North America are more generous to the amateur radio community. The University of Tokyo allows ordinary hams in Japan use XI-IV for taking pictures of the earth after their newer XI-V satellite launched in October 2005. More recently, the Delfi-C3 team turned on their linear transponder. Stations across the world use CW or SSB through this low-power transponder.

2 Common Transceiver Configurations

Arguably, one of the most important parts of any satellite is the communications subsystem. Without any way to communicate, 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 and ruling out any large-scale ground station networks.

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[4]. Two new small companies, AstroDev and ISIS, recently began selling radios designed for CubeSats.

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. The receiver alone requires 1.1 watts of DC power[5, 6]. Other transceivers flown on CubeSats in space include the Alinco DJ-C4 and DJ-C5.

2.3 Custom-Built

Some projects, mainly universities, decide to build the entire transceiver out of individual components. Building a custom communications subsystem allows tighter control of requirements and specifications, and encourages 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, RF Microdevices, and Analog Devices. Other universities go even farther than this by building their entire transceiver at the transistor level, as is the case with Delfi-C3.

2.4 Satellite Comparison

The table below, grouped by launch campaign, shows a summary of the different communications subsystems of the satellites. Only downlink frequencies are listed. **Object** refers to the spacecraft ID number in the NORAD database, available at www.space-track.org. For **Rate/Modulation**, please remember that the symbol rate (baud) is not necessarily the same as data rate (bps), and cannot be directly compared. **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. **Lifetime** refers to the length of the useful life of the satellite. Blank cells indicate the information not known as of November 2008.

Table 1: Summary of spacecraft transmitters.

Satellite	Object	Size	Radio	Frequency	License	Power	TNC	Protocol	Baud Rate/Modulation	Downloaded	Lifetime	Antenna
AAU1 CubeSat	27846	1U	Wood & Douglas SX450	437.475 MHz	amateur	500 mW	MX909	AX.25, Mobitex	9600 baud GMSK	1 kB	3 months	dipole
DTUsat-1	27842	1U	RFMD RF2905	437.475 MHz	amateur	400 mW		AX.25	2400 baud FSK	0[1]	0 days	canted turnstile
CanX-1	27847	1U	Melexis	437.880 MHz	amateur	500 mW		Custom	1200 baud MSK	0[1]	0 days	crossed dipoles
Cute-1 (CO-55)	27844	1U	Maki Denki (Beacon) Alinco DJ-C4 (Data)	436.8375 MHz 437.470 MHz	amateur amateur	100 mW 350 mW	PIC16LC73A MX614	CW AX.25	50 WPM 1200 baud AFSK	N/A >10 MB	65+ months	monopole monopole
QuakeSat-1	27845	3U	Tekk KS-960	436.675 MHz	amateur	2 W	BayPac BP-96A	AX.25[2]	9600 baud FSK	423 MB	7 months	turnstile
XI-IV (CO-57)	27848	1U	Nishi RF Lab (Beacon) Nishi RF Lab (Data)	436.8475 MHz 437.490 MHz	amateur amateur	80 mW 1 W	PIC16C716 PIC16C622	CW AX.25	50 WPM 1200 baud AFSK	N/A >11 MB	65+ months	dipole dipole
XI-V (CO-58)	28895	1U	Nishi RF Lab (Beacon) Nishi RF Lab (Data)	437.465 MHz 437.345 MHz	amateur amateur	80 mW 1 W	PIC16C716 PIC16C622	CW AX.25	50 WPM 1200 baud AFSK	N/A	36+ months	dipole dipole
NCube-2	28897[3]	1U		437.505 MHz	amateur			AX.25	1200 baud AFSK	0[1]	0 days	monopole
UWE-1	28892	1U	PR430	437.505 MHz	amateur	1 W	H8S/2674R[4]	AX.25	1200/9600 baud AFSK		0.75 months	end-fed dipole
Cute-1.7+APD (CO-56)	28941	2U	Telemetry Beacon Alinco DJ-C5	437.385 MHz 437.505 MHz	amateur amateur	100 mW 300 mW	H8S/2328[4] CMX589A	CW AX.25/SRLL	50 WPM 1200 AFSK/9600 GMSK	N/A <1 MB	2.5 months	dipole dipole
GeneSat-1	29655	3U+	Atmel ATA8402 (Beacon) Microhard MHX-2400	437.067 MHz 2.4 GHz	amateur ISM	500 mW 1 W	PIC12C617 Integrated[5]	AX.25 Proprietary	1200 baud AFSK	N/A 500 kB	3 months	monopole patch
CSTB1	31122	1U	Commercial[6]	400.0375 MHz	Experimental	<1 W	PIC	Proprietary	1200 baud AFSK	6.77 MB[7]	19+ months	dipole
AeroCube-2	31133	1U	Commercial[6]	902-928 MHz	ISM	2 W	Integrated[5]	Proprietary	38.4 kbaud	500 kB	0.25 months	patch
CP4	31132	1U	TI CC1000	437.325 MHz	amateur	1 W	PIC18LF6720	AX.25	1200 baud FSK	487 kB	2 months	dipole
Libertad-1	31128	1U	Stensat	437.405 MHz	amateur	400 mW		AX.25	1200 baud AFSK	0[8]	1 month	monopole
CAPE1	31130	1U	TI CC1020	435.245 MHz	amateur	1 W	PIC16LF452	AX.25	9600 baud FSK	0[9]	4 months	dipole
CP3	31129	1U	TI CC1000	436.845 MHz	Experimental	1 W	PIC18LF6720	AX.25	1200 baud FSK	2.0 MB[7]	19+ months	dipole
MAST[10]	31126	3U	Microhard MHX-2400	2.4 GHz	ISM	1 W	Intgrated[5]	Proprietary	15 kbps	>2 MB	0.75 months	monopole
Delfi-C3 (DO-64)	32789	3U	Custom Beacon Custom Transponder	145.870 MHz 145.9-435.55 MHz	amateur amateur	400 mW 200 mW	PIC18LF4680 N/A	AX.25 Linear	1200 baud BPSK 40 kHz wide	60 MB[11] N/A	7+ months	turnstile turnstile
Seeds-2 (CO-66)	32791	1U	Musashino Electric (Beacon) Musashino Electric (Data)	437.485 MHz 437.485 MHz	amateur amateur	90 mW 450 mW		CW AX.25	 1200 baud AFSK	N/A 500 kB	7+ months	monopole monopole
CanX-2	32790	3U	Custom S-Band	2.2 GHz	Space Research[12]	500 mW	Integrated	NSP	16kbps-256kbps BPSK	250 MB	7+ months	patch
AAUSAT-II	32788	1U	Holger Eckhardt (DF2FQ)	437.425 MHz	amateur	610 mW	PIC18LF6680	AX.25	1200 baud MSK	8 MB[13]	7+ months	dipole
Cute 1.7+APD II (CO-65)	32785	3U+[14]	Invax (Beacon) Alinco DJ-C5 (Data)	437.275 MHz 437.475 MHz	amateur amateur	100 mW 300 mW	H8S/2328 H8S/2328, CMX589A	CW AX.25/SRLL	50 WPM 1200 AFSK/9600 GMSK	N/A 21 MB[15]	7+ months	monopole monopole
Compass-1	32787	1U	BC549 (Beacon) Holger Eckhardt (Data)	437.275 MHz 437.405 MHz	amateur amateur	200 mW 300 mW	PIC12F629 C8051F123, FX614	CW AX.25	15 WPM 1200 baud AFSK/MSK	N/A <1 MB	7+ months	dipole dipole

[1] Satellite never heard from in space.
[2] Used a modified Pacsat protocol on top of AX.25. Source code available upon request.
[3] This object separated from SSETI Express months later and is presumed to be NCube-2.
[4] This is also the main satellite processor.
[5] The radio module accepts serial data and uses an internal TNC.
[6] The manufacturer and model number is unknown.
[7] As of April 2008.
[8] No uplink commands received by spacecraft.
[9] The CAPE1 team knew the receiver was dead before integration but had no time to fix it.
[10] One identical radio per satellite section, so three total radios onboard.
[11] Since no on-board telemetry storage exists on this satellite, this figure is not for commanded data and cannot be directly compared to the other spacecraft. This figure is beacon data and includes duplicate beacons.
[12] This is the first CubeSat with a licensed frequency in the 2200 to 2290 MHz Space Research band. Internationally coordinated.
[13] This figure includes all data from the spacecraft, including beacons, bad packets, and retransmissions.
[14] This satellite does not technically count as a CubeSat, as the actual size is 11.5cm x 18cm x 22cm, but is based on the earlier CubeSat designs.
[15] This includes 7 MB from the Tokyo Tech ground station, 5 MB from the Japanese GSN, and 9 MB from amateurs.

3 Satellite Detail

The following sections discuss each CubeSat launched, as of November 2008, in chronological order grouped by launch campaign.

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 at 810 km. 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.

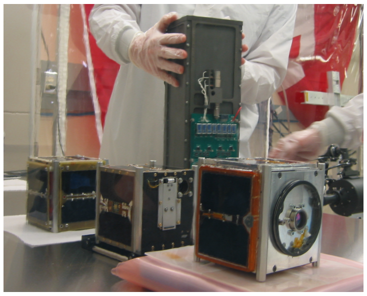

Figure 1: The P-POD Mark I with CanX-1, DTUsat-1, and AAU1 CubeSat in the clean room during integration in Toronto.

3.1.1 AAU1 CubeSat

The first satellite built by Aalborg University of Denmark, AAU1 CubeSat's goal included educating students about satellites and giving them hands on experience with picosatellite technology. AAU1 CubeSat's payload included a camera and various other sensors. Radio amateurs could barely receive the beacon, and only limited amounts of data have been downlinked[7].

The satellite's communications subsystem used a center-loaded dipole antenna for transmit and receive. Transmitter output power is 500 mW with GMSK modulation. Onboard forward error correction increased the link reliability but decreased data throughput. The system uses a 9600 baud rate for communications.

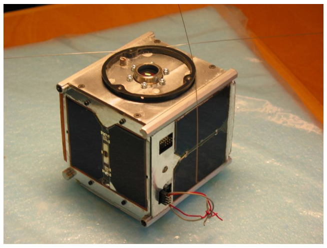

Figure 2: AAU flight model.

Using a MX-COM MX909 TNC chip, this satellite used a Mobitex packet encoding scheme underneath standard AX.25 packet format. These packets contained telemetry data but could not be decoded by regular amateur radio operators due to the proprietary Mobitex packet encoding[8].

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 three months due to battery problems. The team theorizes that a short circuit in the antenna reduced the radiated energy. The university's ground station, consisting of an Icom 910 radio and Yaesu G-5500 rotor, only received about 1 kB of data[9].

3.1.2 DTUsat-1

Students from the Technical University of Denmark built DTUsat-1 with the primary purpose of education. The goal of the primary payload consisted of testing a new and innovative tether deployment system with a 450 meter electrodynamic tether. The design of the tether will force the satellite to slowly deorbit. The secondary payload included a calibrated test transmitter and camera, neither of which flew[10].

The communications subsystem of this satellite included a custom-built transceiver built around an RF Microdevices RF2905, an all-in-one transceiver chip designed for ISM devices. The data rate is 2400 baud, with an output power of 400 mW in the 70cm amateur band[11].

Instead of the common tape-measure antenna, this satellite used solid 2 mm diameter rods of aluminum. A square route consumed one whole side (left panel in Figure 3), 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, and the antenna is released by a nichrome wire melting a string holding the antenna in place[10].

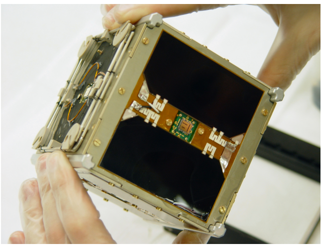

Figure 3: DTUsat-1 in the clean room before integration[10].

Due to perceived import regulations, the team brought DTUsat-1 to Canada in multiple pieces for integration. 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 the world 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 the University of Toronto's Institute for Aerospace Studies contained several payloads. Two Agilent cameras, one black-and-white and one color, were designed to take pictures of the stars and horizon for attitude determination. Active magnetorquers allowed the spacecraft to aim the cameras. The plan also included a COTS

GPS receiver for location and an ARM9 microprocessor for controlling the satellite[12].

As with many CubeSats today, this satellite used a single transceiver in the UHF amateur satellite band[13]. 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 made 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[14].

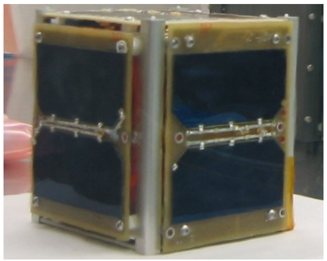

Figure 4: CanX-1.

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 entire P-POD, replacing the mass model with the finished satellite. No vibration tests were performed on the finished satellite. After they finished the satellite, the team focused their energy on building the ground station.

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[14].

3.1.4 Cute-1 (CO-55)

The first CubeSat from Tokyo Institute of Technology, the Cubical Titech Engineering Satellite performs three missions, including a sensor experiment, deployment test, and a communications experiment[15]. The communications experiment consists 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[16].

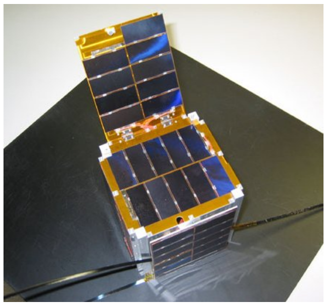

Figure 5: Cute-1 flight model.

The communications subsystem includes a 2m receiver, a 70cm 1200 baud FM transmitter, and a 70cm CW transmitter. 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 with an output of 100 mW. It operates almost continuously, making it very easy to track[17].

The 2m 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 70cm amateur band. Nominal power 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[17].

Cute-1 still operates today, more than 65 months after launch. The operations team is currently focused on Tokyo Tech's newer satellites.

3.1.5 QuakeSat-1

Stanford University and QuakeFinder LLC collaborated on this 3U CubeSat designed to measure signal amplitudes in the VLF range. This satellite used a underclocked 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. The amplifier produced 2 watts of RF power and is 23% efficient. This satellite used a Tigertronics BayPac BP-96A hardware TNC[19].

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 power cycled the satellite several times to rescue it from a locked state[20].

When on, this satellite beaconed a short 200 byte packet every 10 seconds, making it a really easy to find 9600 baud source in space. The downlink protocol used 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 seven months after launch, this satellite turns off for eclipse and must be manually controlled back on, making this source less reliable today.


Figure 6: QuakeSat-1 model on display[21].

While this paper does not intend to describe payloads aboard these satellites, this payload is of interest because it was 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; 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 scientific results[21].

QuakeSat-1 also used two ground stations linked via the internet to download more data[22]. 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 University would start 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 November 2008[20].

3.1.6 XI-IV (CO-57)

This 1U CubeSat from the Intelligent Space Systems Laboratory at the University of Tokyo is the first in the XI (pronounced "sai") series to fly in space. The first three "satellites" were built as bench models. The mission of this spacecraft includes student education and verification of a working satellite bus for future missions. The payload consistes of a small cellphone-type camera, seen under the kapton tape in Figure 7.

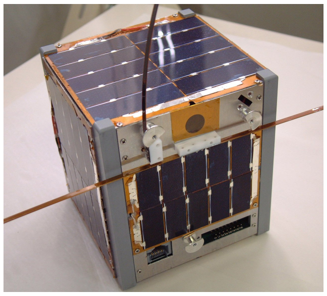
Figure 7: XI-IV in the cleanroom.

The custom built communications subsystem includes one uplink receiver, one beacon transmitter, and one telemetry transmitter. The TNCs consist of various different PIC16 microcontrollers, and the transmitters and receivers comprise of custom chips from Nishi RF Lab with 1 watt of output power[23].

Much like Cute-1 (Section 3.1.4), the CW beacon operates almost continuously. Six different CW messages rotate through all pertinent telemetry data, including on-board computer status, temperatures, voltages, and currents[24]. The almost continuous beacon makes it a good reference for testing ground station performance.

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 2m and two phased yagis on 70cm[25].

Since the University of Tokyo is more interested in operating their newer XI-V satellite(Section 3.2.1), they have graciously let ordinary amateur satellite operators in Japan, and students at Cal Poly State University, command the satellite to take pictures. An online schedule permits amateurs to take pictures and store them in memory for later download.


Figure 8: Earth picture taken by XI-IV.

While some of the picture storage memory on the satellite no longer works, the rest of the satellite operates beautifully to this day, more than 65 months after launch. 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[26, 27].

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 three CubeSats inside. Sponsored by the European Space Agency Education Office, this satellite brought together many universities across Europe, educated hundreds of students, and caught the attention of millions of people.

SSETI Express failed almost immediately after launch. One transistor, designed to keep the batteries from overcharging, failed soon after launch, shorting the solar panels to ground. The satellite operated on batteries for a few days, and ground stations downloaded 8 kB of telemetry. The T-PODs, from the University of Tokyo, 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 until much later[28].

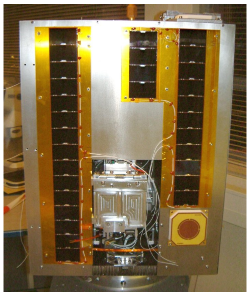

Figure 9: SSETI Express during construction. One T-POD door is visible in the center of the picture and the other two T-PODs are on other sides of the spacecraft. The S-band patch antenna is visible in the lower right corner.

3.2.1 XI-V (CO-58)

XI-V began life as an engineering model of XI-IV. Consequently, it contains exactly the same electronics and payload as XI-IV, and operates in exactly the same way[23]. The only differences are different solar cells for space testing, new software, and a higher-resolution camera.

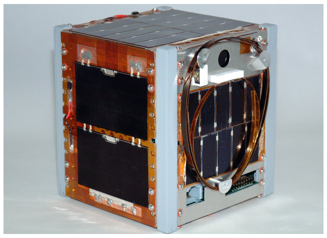

Figure 10: XI-V.

The hardware for 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 more than 36 months after launch. Students at the University of Tokyo and others still download pictures regularly, despite problems with the camera. 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) receiver and attitude determination and control experiment. NCube-2 was launched on SSETI Express, but it is unclear whether NCube-2 ever ejected from SSETI. During integration and vibration testing, NCube-2's gravity boom prematurely deployed into SSETI Express several times[29].

NCube-2's uplink and downlink operated on two different frequencies bands. The command receiver listened on 2m and the downlink transmitted on 70cm. The 2m receiver used a dipole antenna, and the 70cm transmitter used a quarter wave monopole antenna[30]. The original design of NCube-2 included an L-Band transmitter for downlink and a GPS receiver, but these experiments were not included in the final satellite.

Since NCube-2's mission included receiving and retransmitting AIS signals, NCube-2 included commercial AIS hardware. Although the AIS system uses both 161.975 MHz and 162.025 MHz, the NCube-2 team decided to simplify their design and receive only one of the frequencies. The TNC chosen for the task of decoding the AIS signals was a MX589TN high-speed GMSK modem. No signals were ever heard from NCube-2[31].

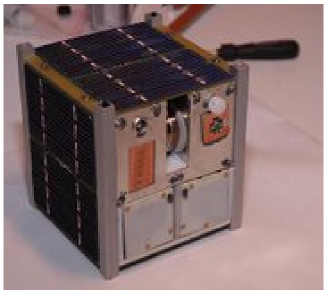

Figure 11: NCube-2.

3.2.3 UWE-1

This satellite, from the University of Würzburg in Germany, was designed to test TCP/IP protocols in space and the effects of low bandwidth, long path delays, and dropped packets[32]. The university built an internet-to-satellite gateway that allowed users on the internet to access the satellite much like a networked hard drive. A secondary payload tested high efficiency solar cells.

The main processor included a Hitatchi H8S/2674R microprocessor running µClinux. Magnetic torquers allowed spacecraft stabilization on two axes, with the antenna as a gravity gradient on the other axis. Using temperature and currents from the solar panels, satellite rotation rates of around 2.1 revolutions per minute around the antenna axis were calculated[33].

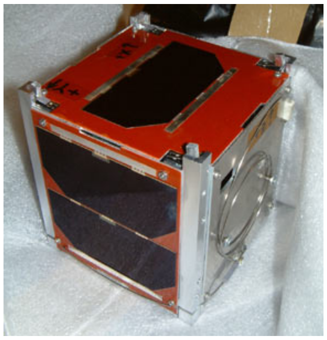

Figure 12: UWE-1.

The satellite used a SR-Systems PR430 transceiver with built-in TNC[34]. However, the main processor performed all the TNC functions, packetizing all the data into the AX.25 frame. It then sent these frames using the 6pack protocol (similar to KISS) to the TNC. This allowed the main processor to control the Data Link

Layer settings of the radio, improving system performance.

This satellite beaconed once a minute with a short 1200 baud AFSK packet. The university ground station had trouble receiving the satellite in the first few days after launch due to faulty ground equipment and weather. Luckily, numerous other ground stations around the world received these beacons and forwarded the data on to the university[35]. This data showed that the satellite was stable and working well. Within a week, the university fixed the ground station, and normal operations ensued. UWE-1 stopped functioning in November 2005, about three weeks after launch.

3.3 M-V-8 Launch

This sixth launch of the M-V rocket, sponsored by JAXA, launched the first CubeSat from the Uchinoura Space Center in Japan on 22 February 2006. The primary payload included ASTRO-F, a 955 kg infrared astronomy satellite. Students expect Cute-1.7+APD, placed in a 700 x 300 km polar orbit, to deorbit within a few years[36].

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

3.3.1 Cute-1.7+APD (CO-56)

Figure 14: Cute 1.7+APD.

Cute-1.7+APD, built by Tokyo Tech University, completely redesigned the Cute-1 bus around common consumer electronics. Two Hitachi NPD-20JWL PDAs, 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[37].

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

This satellite contained two receivers and two transmitters. The command uplink receiver listened in the 2m amateur radio band, and the store-and-forward message box listened at 1200 MHz. Both the CW beacon and data transmitters resided in the 70cm amateur band. The data transmitter switched between 1200 baud AFSK packet and 9600 baud GMSK packet depending on the satellite mode. The L-band uplink allowed the satellite to operate as a store-and-forward packet satellite, open to the public. This satellite allowed Simple Radio Link Layer packets as well as AX.25[38].

This satellite started functioning erratically in the end of March 2006, when the battery voltage started slowly dropping. Ground testing indicated that a single-event latchup would cause similar problems, but due to a miscalibration in the smart fuse circuit this fault would not get cleared. Battery voltage continued dropping for ten days, when it became so low that the satellite shut down. Seven days after brownout, the satellite entered eclipse, and whatever device shorting the power bus reset. The satellite started functioning normally again. However, in May 2006 the same problem arose and the satellite never recovered. Currently, it transmits an unmodulated carrier on the UHF data frequency. This condition will likely continue until the batteries fail[39].

3.4 Dnepr Launch 1

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

The CubeSats, all 1U except one, performed many different science experiments. MEROPE, from Montana State University, measured the Van Allen belts around our planet. The University of Hawaii's Voyager CubeSat contained a 5.8 GHz phased-array antenna. ICE Cube 1 from Cornell University received GPS signals in space. Rincon and Sacred, from the University of Arizona, measured radiation levels.

This launch failed on 26 July 2006, devastating the CubeSat community. Fourteen CubeSats ended up in terrasynchronous orbit after the rocket motor turned off 73 seconds into launch. Pieces of satellites were found 30 miles from the launch site, and the first stage blasted a 50 meter crater on the steppes of Kazakhstan[40, 41, 42].

3.5 Minotaur Launch 1

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, the P-POD fired backwards after the motor turned off.

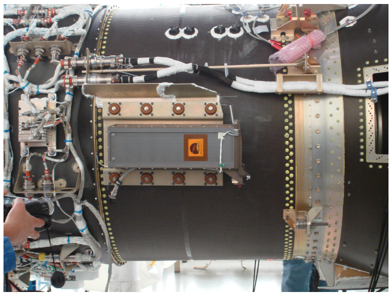

Figure 15: The P-POD Mark II, with GeneSat-1 inside, strapped to the side of the Minotaur Launch Vehicle upper stage motor casing. The third stage at right fell away before the satellite ejected.

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 included 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[43].

The entire GeneSat-1 bus consumed 1U of this satellite. As part of the educational outreach objective, the 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 transmit power was 1 W with an overall efficiency of 22%. This radio used a proprietary packet format with GFSK on top of frequency hopping spread spectrum.

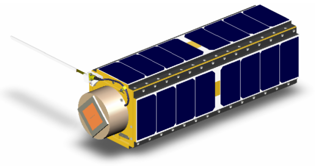

Figure 16: GeneSat-1 showing the 2.4 GHz patch antenna and UHF beacon assembly on the end[5].

To communicate with the satellite at 10 degrees above the horizon, the link budget required a 60-foot diameter dish for a 10 dB margin. The project used SRI International's dish at Stanford University. Before it could be used at 2.4 GHz, the dish needed several modifications, including the installation of new mesh and construction of a weatherproof case to house the Microhard radio at the feedpoint. The GeneSat-1 team downloaded about 500 kB of telemetry with the Microhard radio[5]. Overall, the radio performed poorly as two-thirds of the passes with the 60-foot dish resulted in no communications with the spacecraft.

The GeneSat project also sponsored an amateur radio contest. Whoever decoded the most beacons during the experiment phase could donate a complete ground station to any university of their choosing. Kevin Schuchmann, WA6FWF, of California won the contest with the most beacons heard.

The beacon transmitter, built by the Stensat group, used a PIC12C617 to convert the serial data into an AX.25 packet for transmission. The transmitter contained an Atmel ATA8402 and an RF Microdevices amplifier for 500 mW of output power into a monopole antenna. Since the Atmel chip supported only FSK modulation, the beacon designers modulated the crystal input to generate standard FM AFSK modulation signals[44].

For future missions, such as PreSat and PharmaSat, the team will test the next version of the Microhard radio and experiment with smaller dishes[45].

3.6 Dnepr Launch 2

The Dnepr Launch 2 blasted off from Baikonur Cosmodrome in Kazakhstan on 17 April 2007. Unlike the first Dnepr launch, this one successfully deployed three 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 switch the entire rocket with a new one, delaying the launch by one month. After reintegration of the Space Head Module onto the new rocket, it flew at 06:46 UTC.

Figure 17: The first P-POD Mark II with MAST inside mounted to the Space Head Module. The other two P-PODs will be mounted on the same mounting plate.

3.6.1 CSTB1

This 1U CubeSat from The Boeing Corporation contains a camera and a magnetometer for measuring attitude. It also contains 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.

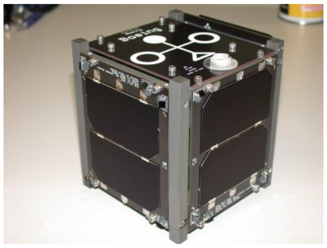

Figure 18: CSTB1. Photo reprinted with permission of The Boeing Corporation.

CSTB1 uses two commercial transceivers for the communications subsystem, transmitting with an experimental license at 400.0375 MHz. A custom antenna switch allows 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 work as redundant TNCs.

This satellite, operating at 1200 baud, downloaded 6.77 MB of picture and telemetry data as of April 2008. It still works well, and the deorbit mechanism has deployed and is functioning nominally[46].

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 21).

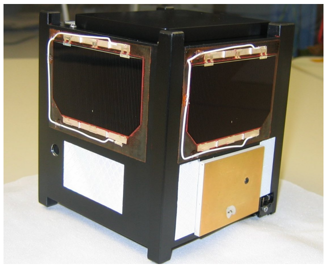

Figure 19: AeroCube-2 before integration. Photo reprinted with permission of The Aerospace Corporation.

The communications subsystem of this satellite comprised of a commercial ISM 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[47].

When commanded, the satellite transmited through an omnidirectional patch antenna to the 60-foot dish at SRI International in Menlo Park, CA. This ground station 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 about one week after launch[47].

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.

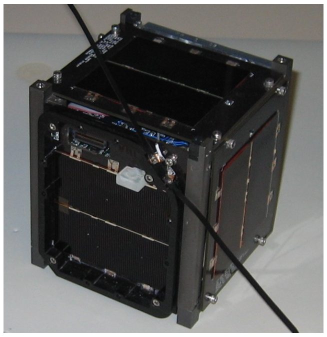

Figure 20: CP2 Flight 2. Blue wire mods are visible on the C&DH board.

This satellite used an 8-bit PIC18LF6720 as the C&DH microcontroller. The clock speed is 4 MHz, and a single I^2C bus snaked all over the satellite with an I^2C MUX device for device failure isolation and bus address conflict resolution[48, 49]. 128kB of redundant external memory, addressed over the I^2C bus, augmented the 128k of memory inside the PIC microcontroller. Power came from dual-junction solar panels on five sides of the satellite[50].

The communications subsystem contained two identical radios. Each radio contained a PIC18LF6720 processor, a Chipcon CC1000 single-chip transceiver programmed for 437 MHz, and an RF2117 one watt amplifier. The PIC processor for each radio converted the data from the C&DH into a standard 1200 baud AX.25 frame, programed the CC1000 with the correct frequency and power output, and regulated the start-up sequence of the RF2117 amplifier chip[51, 52].

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 well, but only above elevations of 30 degrees would the satellite sometimes respond to commands. Also, it appeared that long commands sent to the payload did not work most of the time, possibly due to bit flips in the transmissions up to the satellite.

Figure 21: CP4 in space. This picture was taken by AeroCube-2 (Section 3.6.2) a few minutes after ejection from the P-POD.

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 2m and 70cm yagis. Both fully independent stations use software TNCs and Yaesu G-5500 rotors. The total data downloaded from CP4 is approximately 487 kB.

CP4 partially failed in orbit after about two 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^{2}C bus failed, causing all internal communications to cease. The I^{2}C bus on the satellite always had problems, mostly caused by very high board capacitance.

The satellite came back to life about one year after launch with approximately 600 processor resets during its time away. Other than that, the spacecraft was fine with batteries fully charged. The team is not quite sure why it came back to life, but two months later it went silent again.

3.6.4 Libertad-1

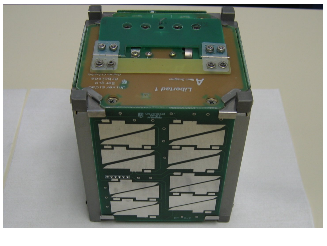

Figure 22: Libertad-1 during integration into the P-POD.

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[53]. Libertad-1, the first in the "Colombia en órbita" project, generated lots of interest and excitement across the country. It motivated many people to consider engineering as a future career path.

This satellite used a structure and main processor from a CubeSat Kit from Pumpkin Inc. 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[54].

A standard Stensat radio formed the heart of the communications subsystem, with uplink on 2m and downlink on the 70cm amateur radio band. The beacon consisted of a five AX.25 packet burst every 10 minutes, with internal side panel and microcontroller temperatures as the only telemetry[4]. This long period frustrated listeners, as an entire pass could pass 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[55]. 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.

This satellite transmitted two beacons, a 30 second CW preamble followed by a short 9600 baud packet burst, 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 encoding or 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 satellite health knowledge. Amateur radio operators listening to the VHF downlink of VO-52 heard CAPE1's beacon through the transponder on numerous occasions.


Figure 23: CAPE1. The turnstile antenna doors are visible above the solar cells.

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. No uplink commands were successfully decoded by the satellite. CAPE1 died four months after launch, but recently revived itself in March 2008. It beacons intermittently[56].

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 2.0 MB of data has been downloaded from CP3 as of November 2008.

CP3 also suffers from poor receive sensitivity, as the communications subsystem is a replica of CP4. 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[57].

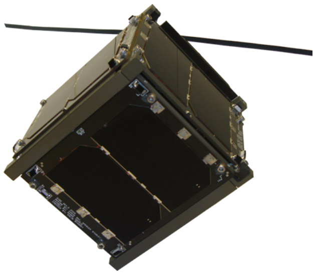

Figure 24: CP3.

This satellite still functions in orbit, but for an 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 Tethers Unlimited Inc, 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[58].

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.

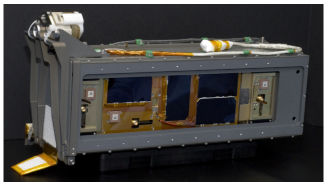

Figure 25: MAST inside a P-POD[6].

The communications subsystem aboard each of the three sections comprised of a 2.4 GHz Microhard MHX-2400 transceiver[6]. 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 for the dish operator.

Communication issues prevented these satellites from completing their mission. The Aerospace Corporation had previously booked the SRI dish, so no communication attempts with MAST occurred for the first three days after launch. During these three days, the satellites’ receivers were on continuously, draining the batteries to critical states. While in receive mode, the Microhard consumes around 1.1 watts of power. This may be acceptable for a triple cube, but a single cube has trouble generating this amount of power[59].

With the batteries discharged, the main processor forced the receivers to turn off, except for during 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. Two of the sections were never heard from, and the third died three weeks after launch[6].

3.7 PSLV-C9 Launch

The first CubeSat launch from India, the Polar Satellite Launch Vehicle launched on 28 April 2008 with 10 satellites aboard, including two large satellites, two nanosatellites, and six CubeSats. The rocket weighed 230 tons, or almost 50 elephants, and launched from Chennai, on the country's east coast[60]. The rocket went into a 635 km polar orbit at 97.9 degrees[61].

Integration into the X-PODs occurred in Toronto in the middle of August 2007. The teams arrived in India at the beginning of April 2008 and began getting the satellites and X-PODs ready for launch vehicle integration. One launch complex employee continuously swept and vacuumed the clean room floor. The launch went flawlessly, and all CubeSats on this launch continue to work in November 2008.

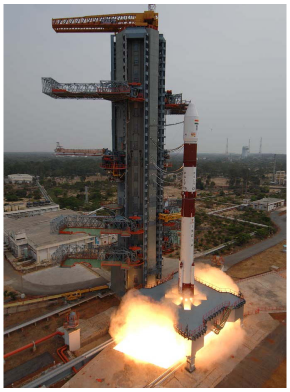

Figure 26: PSLV C9 during liftoff[61].

3.7.1 Delfi-C3 (DO-64)

The first CubeSat built by students at Delft University of Technology, Delfi-C3 contains two payloads. Thin film solar cells, donated by Dutch Space for flight testing, reside on the end of the solar panel deployables. Autonomous wireless sun sensors, located on each end and using a 915 MHz Nordic nRF9E5 for communication to the bus, provide attitude determination and are flown for flight qualification. The communications subsystem of this satellite contains a custom-built BPSK telemetry transmitter and a linear transponder, both technologies flying for the first time on a CubeSat[62]. The satellite contains 17 Microchip PIC18LF4680 microprocessors for all the various subsystems[63].

This satellite contains no batteries, so this satellite resets once per orbit. The on-board computer and command uplink receivers are always on when in the sunlight. The team thoroughly tested the spacecraft's boot-up sequence, but even with all the testing the satellite sometimes abruptly turned off the downlink due to a non-critical databus issue. This issue was worked around with an on-orbit software update.

This spacecraft contains two radios, each containing a command uplink receiver and BPSK telemetry transmitter. One radio also contains a linear transponder that shares the IF stage with the BPSK system.

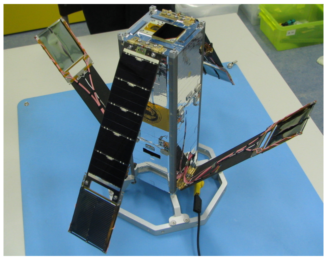

Figure 27: Delfi-C3 after thermovac[64]. The wireless sun sensor resides on the top and bottom, and the thin film solar cells are separated at the ends of the deployables.

The telemetry transmitter consists of an entirely custom-built 1200 baud BPSK transmitter. The team selected the BPSK modulation scheme because of the lower signal-to-noise ratio requirements and ease of decoding with a computer sound card. It uses the standard AX.25 packet format. The BPSK signal is generated in a double-balanced mixer with shaped bits, similar to the method used on AO-16[65, 66].

The Delfi-C3 team released telemetry decoding software, RASCAL, which allowed regular amateur radio operators to decode this new modulation scheme. The RASCAL software listened to the computer's sound card and graphically represented satellite health with gauges. The software also forwarded this data to Delfi-C3 Mission Control, and allowed the team to get an almost real-time status of the spacecraft around the world. This software excited many hams, who forwarded more than 60 MB of telemetry to the team. Since this satellite does not contain on-board telemetry storage, this distributed ground station network is crucial for the Delfi-C3 team to understand the health of the satellite and gather payload data.

When in transponder mode, the satellite acts just like a very low power linear transponder. The satellite transmits a CW beacon 10 kHz lower than the passband, at 10 dB down from the main signal. With a similar message to the original Sputnik satellite, the CW beacon uses double sideband modulation. Be sure to use a good ground station, as the hearing-challenged satellite transmits only 400 mW.

During the annual AMSAT-UK Colloquium at the University of Surrey in July 2008, the Delfi team permanently placed their satellite in transponder mode. Ordinary amateur radio operators now use the spacecraft for SSB and CW contacts, although the very low power of the transmitter makes it difficult for weak or deaf stations. During the Colloquium, several ordinary amateurs made contacts thorough the satellite, but the hand-held stations at the Colloquium didn't have enough power to use the transponder for voice contacts.

3.7.2 SEEDS-2 (CO-66)

Originally developed for the Dnepr Launch 1 in September 2004, this first satellite from Nihon University contains several sensors and a Digi-Talker as the primary payload, similar to FO-29[67]. The sensors include 3-axis gyros and magnetometers. When the Dnepr 1 launch failed, the team upgraded the extra engineering unit to flight status and added slow-scan TV (SSTV) functionality to the Digi-Talker.

This satellite contains one transmitter and one receiver, built by Musashino Electric Machine Ltd., each with their own separate monopole antennas[68]. When transmitting CW, the output power is 90 mW, and the FM Digi-Talker/SSTV transmitter output is around 450 mW. Many people around the world received and decoded the SSTV transmissions[69].

The Nihon University Ground Station contains four phased UHF antennas for downlink and one VHF yagi for uplink, and an Icom 910D transceiver. The station, along with 12 other university stations, also participates in the Japanese Ground Station Network. The ground station has downloaded 500 kB of data[70].

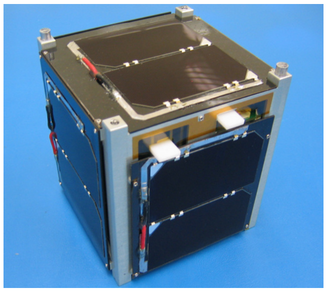

Figure 28: Seeds-2[69].

3.7.3 CanX-2

The second CubeSat from The University of Toronto's Space Flight Laboratory, CanX-2 tests critical technologies for future CanX satellites. Developed in 2 years, this satellite includes experiments such as propulsion, imagers, attitude determination and GPS[71]. The main processor consists of a 12 MHz ARM7.

This satellite contains a UHF command transceiver. It operates with a 4 kbps GMSK modulation scheme in the 70cm amateur radio band using a canted quad antenna system. The UHF transmitter portion has never been turned on because the S-band transmitter works much better.

The primary downlink consists of a custom built S-band transmitter. It puts out 500 mW with a BPSK or QPSK modulation scheme. The data rate is variable between 8 kbps and 1.024 Mbps, but their license restricts the signal bandwidth to 500 kHz, or a maximum of 256 kbps. Early plans included a VHF transmitter, but this was scrapped due to space constraints. CanX-2 uses the Nanosatellite Protocol (NSP), a custom protocol with flight heritage from their earlier MOST space telescope mission[73].

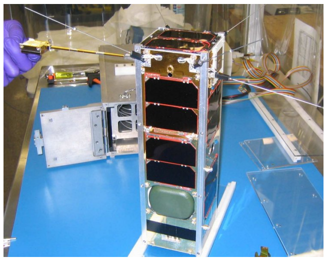

Figure 29: CanX-2 with the X-POD in the background[72].

CanX-2 uses the licensed Space Research spectrum between 2200 and 2290 MHz. The Canadian Radio-television and Telecommunications Commission and International Telecommunications Union coordinates these frequencies, and it took 4 years for the team to obtain a frequency. The ground station consists of a tripod with dual phased UHF high-gain yagis, and a tower with a single VHF yagi and 2.1 meter dish with S-band feed[74].

3.7.4 AAUSAT-II

AAUSAT-II is the second satellite from Aalborg University, Denmark. AAUSAT-II's primary mission is to space test a gamma radiation detector from the Denmark National Space Institute. The main processor consists of an ARM7 Atmel AT91SAM7A1, operating at around 60°C. Currently, the satellite produces a lot of power, spins around 30 RPM, and the main computer reboots every one to four hours[75].

AAUSAT-II uses a custom-built transceiver from Holger Eckhardt. A PIC18LF6680 performs data packetization and sends the data to the modem chip via USART. The modulation scheme is MSK, generated by a CML Microcircuits CMX469A chip. This chip can be configured to work at either 1200, 2400, and 4800 baud, although the system defaults to 1200 baud[76].

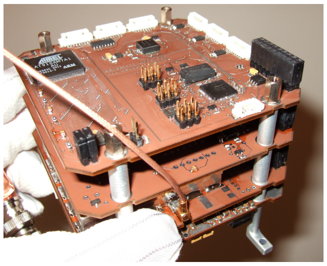
Figure 30: AAUSAT-II[77].

After launch, the team noticed that the satellite was not hearing the ground station at all. Two months after launch the team finally communicated with their satellite with a borrowed 400 watt amplifier. Shortly after they established contact with their spacecraft, it was apparent that it was rotating very quickly, around 24 RPM, and slowly increased to 60 RPM over the next month and a half. It is unclear what caused the increasing rotation, but some speculate that a short in a loop of wire around one solar panel is torquing the spacecraft. The rate slowed considerably after the team turned on the internal de-tumbling algorithm[77].

The university's ground station consists of two phased medium-gain yagis. After establishing contact with the 400 watt amplifier, the team purchased a 1 kW amplifier, and has not had uplink problems since.

3.7.5 Cute 1.7+APD II (CO-65)

Cute 1.7+APD II is the third picosatellite from the Laboratory for Space Systems at the Tokyo Institute of Technology. The immediate successor to Cute-1.7+APD (section 3.3.1), this satellite shares a lot of the same design as its predecessor, including the same Avalanche Photo Detector (APD) payload. The main processors, inside the dual Hitachi NPD-20JWL PDAs, are a 400 MHz ARV4I. This satellite, however, incorporates several improvements based on lessons learned from the Cute 1.7+APD flight experience.

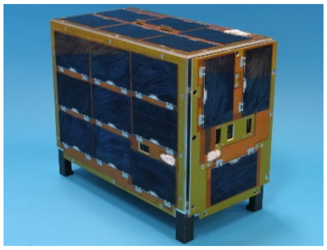
Figure 31: Cute 1.7+APD 2[18].

This satellite differs from Cute 1.7+APD in three main ways[78]. First, the team redesigned the satellite with radiation-tolerant parts to protect the onboard computers from single event latch-ups, possibly the cause of the previous spacecraft's communications failure. Second, the team modified the structure to decrease satellite integration time. The third improvement included addressing the lack of electrical power available onboard by increasing the size of the satellite to allow for more solar cells. This increase in surface area, to a volume of 11.5cm x 18cm x 22cm, meant that the spacecraft would not fit inside the P-POD or X-POD, so the university built a custom separation mechanism. The communications subsystem did not change between the previous satellite and this one[79].

The ground station at Tokyo Institute of Technology has downloaded about 7 MB of data, and the Japanese GSN has collected about 5 MB of data. Ordinary Japanese amateur radio operators have forwarded about 9 MB of data to the university, bringing the total collected data to around 21 MB. However, this figure includes duplicated data, so the actual number may be significantly less[80].

3.7.6 Compass-1

Started in 2004, this CubeSat from the Aachen University of Applied Sciences, Germany, contains a 640 x 480 pixel Omnivision camera for taking pictures of the earth. A Phoenix GPS from the German Space Center and sun sensors control active magnetorquers to orient the spacecraft when the camera takes pictures. The main processor is an Infineon C8051F123 from Silicon Laboratories[81].

This satellite contains one transceiver, custom built by Holger Eckhardt, and one CW transmitter. On receive, a Mitel MT88L70 DTMF decoder chip listens for VHF uplink commands. During transmission, a Silicon Laboratories C8051F123 packetizes the data from the main processor. The radio can send 1200 baud AFSK using a FX614 modem chip. When commanded, it can send 2400 or 4800 baud MSK using a CMX469A modem chip with the AX.25 packet format.

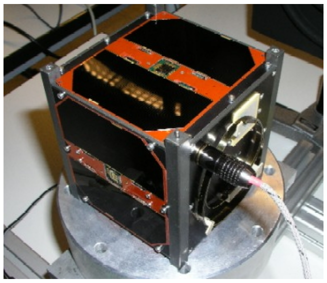
Figure 32: Compass-1.

The CW beacon transmitter uses a custom-built circuit around a BC549 transistor. The output power is about 200 mW. When the satellite started beaconing for the first time, many listeners immediately noticed a large amount of chirp on the signal. This chirp is caused by the on/off switching of the transmitter, which causes the crystal to change it's frequency during transmission. Both Compass-1 and Cute-1.7+APD II share the same beacon frequency, so just after launch one could hear both satellites transmitting at the same time[82].

In September 2008, Compass-1 began having power problems. The satellite tried to heat the batteries constantly, but the batteries could not supply the heater current and the spacecraft shut off once per orbit. The team released the uplink codes to the amateur community with the hopes that somebody could change the temperature set points before the satellite shut down. This attempt succeeded, and the spacecraft operates normally today.

The ground station consists of two phased 2m yagis and four phased 70cm yagis from Tonna, with Icom IC-910H and IC-821H radios. Mike Rupprecht (DK3WN) also helps out with his ground station. The Compass-1 team also operates a ground station in Taiwan[83].

3.8 Falcon Launch 1

On 2 August 2008, SpaceX launched their third test flight of the Falcon 1 from the Kwajalein Atoll in the South Pacific. Unfortunately this flight failed at an altitude of 217 km, after the first stage bumped into the second stage just after separation[84].

This launch carried two 3U CubeSats in two P-PODs. NanoSail-D, from NASA Marshall Spaceflight Center's, attempted to demonstrate the first solar sail propulsion system. Solar sails use energy from the sun to gently push the spacecraft along[85].

The second CubeSat comprised of NASA Ames' Pharmasat Risk Evaluation Satellite (PreSat), a flight test of PharmaSat. Based on GeneSat, this satellite contained sensors to measure the growth of yeast cells in orbit[86].

Figure 33: Upper stage of the Falcon 1 launch vehicle. The P-POD Mark III is mounted in the lower right.

4 Communications Subsystem Recommendations

After writing this paper, we recommend that new satellite developers follow these guidelines:

- Include a long beacon. All Japanese CubeSats are 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 RF power, they are easily received by a common SSB receiver and an omnidirectional whip antenna. Include as much spacecraft data on this beacon as you can so that you 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, tremendously increasing our knowledge of our satellite. Colin Hurst even wrote up a complete attitude determination paper for CP4[87].

However, there are downsides to using common modes. The common 1200 baud data rate is too slow for large amounts of data, the AFSK modulation scheme requires a large signal-to-noise ratio, and there is no forward error correction or compression in the AX.25 protocol. The CubeSat and amateur radio communities need to coalesce around a new "common" mode, one that emphasizes spectral efficiency, data rate, and error correction, and is ideally supported by multiple commercial vendors.

- 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, we might be able to reset the processor and start normal operations 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 Thursdays during the evening passes.

- Don't depend on another ground station to close your communications link. The MAST team couldn't talk with their satellite for three days because another satellite booked the dish they needed. This lack of communication with the dish operators probably caused the mission to fail. Each organization building CubeSats should have full unrestricted access to a local ground station, ideally 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 you're trying to learn about the amateur radio service. Most mentors know a lot about electronics and RF systems. They 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, around 797 MB for 24 satellites over 5 years. Without QuakeSat-1 and CanX-2, this number drops to around 124 MB. 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. Some of those radios are commercially available.

The CubeSat and amateur radio communities also need to jointly develop and agree on a new “common” modulation scheme, with larger data throughput and forward error correction. This standard modulation scheme will allow amateurs and universities to easily 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[88, 89]. 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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