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, modulation schemes, antennas and power outputs are discussed. Commercial off the shelf (COTS) transceivers, modified and unmodified and custom-built transceivers are compared and contrasted. Recommendations for the communication subsystems of new CubeSat projects are presented. In this first part the overall communication system design goals are discussed. The most recently launched fleet of CubeSats is discussed.

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. We provide background information on the CubeSat project and describe how the Amateur Radio and CubeSat communities work together. Next we discuss the common transceiver configurations, including purchasing a COTS transceiver, purchasing then modifying a COTS transceiver and custom-built transceivers. We give some recommendations to new CubeSat developers building a communications subsystem. We will provide a description of the most recently launched CubeSats as most are still operational.

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), a 23 kg nanosatellite. 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 ratings by flying in a CubeSat.

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 due to concerns 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.

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 communicate with 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 to use XI-IV for taking pictures of the earth after their newer XI-V satellite was launched in October 2005. More recently, the Delfi-C3 team turned on their linear transponder. Stations across the world used CW or SSB through this low-power transponder while it was operational.

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.

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 network. 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 2 m receiver and 70 cm 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.

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

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CubeSats: continued from page 23 ...

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.

Custom-Built

Some projects, mainly those built by 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. However, 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 further than this by building their entire transceiver at the transistor level, as is the case with Delfi-C3.

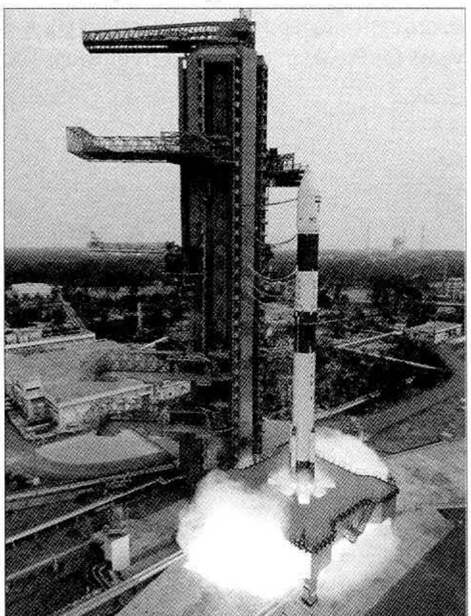

Figure 1: PSLV C9 during liftoff.

Satellite Comparison

Table 1 shows a summary of the different communications subsystems of the satellites. Only downlink frequencies are listed.

PSLV-C9 Launch

The first CubeSat launch from India, the Polar Satellite Launch Vehicle launched on April 28, 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. The rocket went into a 635 km polar orbit at 97.9 degrees [7].

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.

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 [8]. The satellite contains 17 Microchip PIC18LF4680 microprocessors for all the various subsystems [9].

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 data bus issue. This issue was worked around with an on-orbit software update.

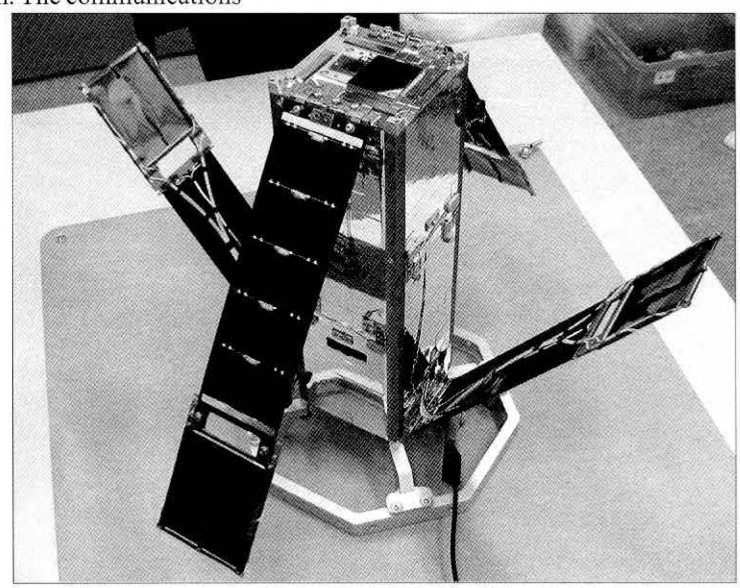

Figure 2: Delfi-C3 after thermovac [10]. The wireless sun sensor resides on the top and bottom, and the thin film solar cells are separated at the ends of the deployables.

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.

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 [11, 12].

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

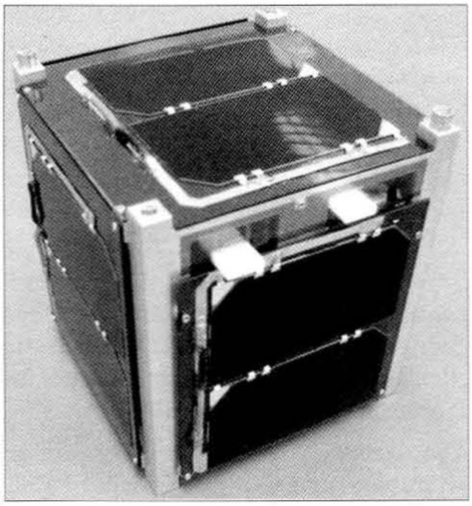

Figure 3: Seeds-2

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. When this mode was active, ordinary Amateur Radio operators used the spacecraft for SSB and CW contacts, although the very low power of the transmitter made 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.

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 [13]. 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 [14]. 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 [15].

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 participate in the Japanese Ground Station Network. The ground station has downloaded 500 kB of data [16].

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 [17]. 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 70 cm 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 [19].

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 [20].

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 [21].

AAUSAT-II uses a custom-built transceiver from Holger Eckhardt. A PIC18LF6680

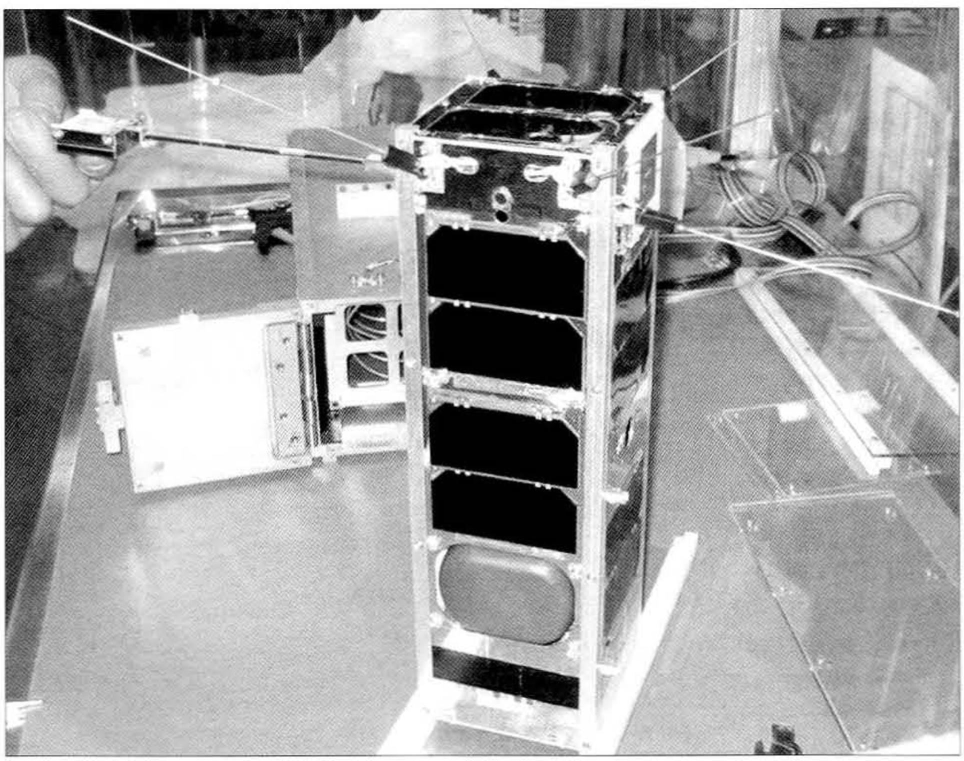

Figure 4: CanX-2 with the X-POD in the background [18].

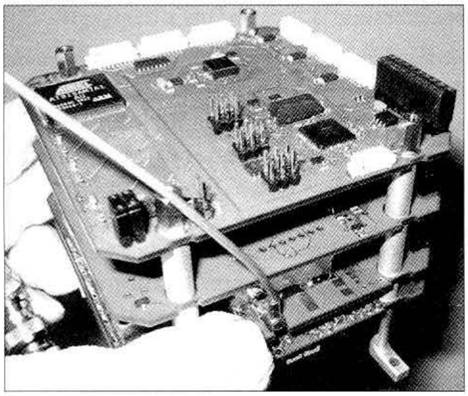

Figure 5: AAUSAT-II

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 [22].

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 [23].

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.

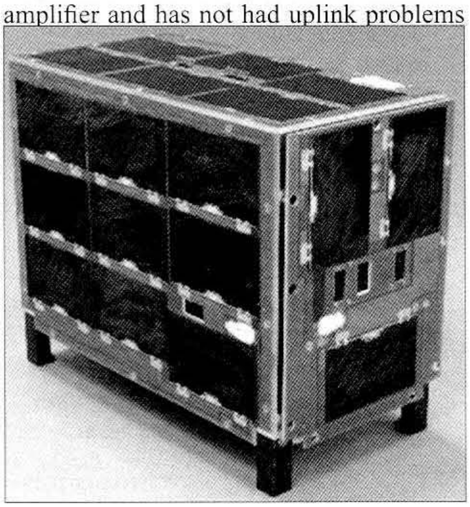

Figure 6: Cute 1.7+APD 2.

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, 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. This satellite differs from Cute 1.7+APD in three main ways [24]. 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 11.5 cm x 18 cm x 22 cm, 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 [25].

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 [26].

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 [27].

This satellite contains one transceiver, custom built by Holger Eckhardt, and one CW transmitter. To 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.

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 [28].

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 2 m Yagis and four phased 70 cm 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 [29].

Communications Subsystem Recommendations

Based upon accumulated experience with

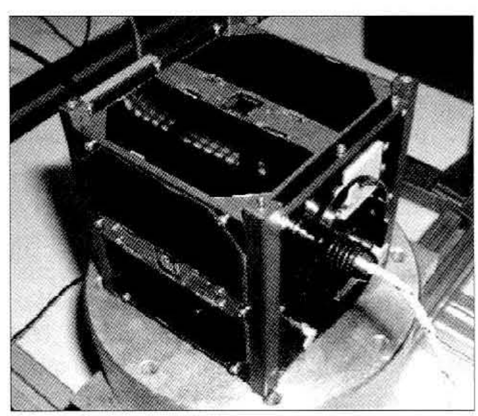

Figure 7: Compass-1.

several CubeSats, we recommend that new satellite developers follow these guidelines:

- Include a long-running 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 [30].

  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 group had 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.

Conclusion

Table 1 shows the low data rates on CubeSat downlinks in orbit right now. Overall, around 797 MB of data have been downloaded from 24 CubeSats over 5 years. Without QuakeSat-1 and CanX-2, the data download drops to around 124 MB 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. 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 [31,32]. It will also allow remote control of satellites from ground stations around the world, greatly increasing satellite health knowledge. GENSO was scheduled to be open to any interested parties in summer 2009.

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Table 1 appears on the next page ...

Table 1: CubeSat Summary (✓indicates currently active)

On Air	Satellite	Size	Radio	Frequency (MHz)	License	Power	TNC Protocol	Baud Rate Modulation	Antenna
	AAU1 Cubesat1	1U	Wood & Douglas SX450	437.475	Amateur	500 mW	AX.25, Mobitex	9600 GMSK	Dipole
	DTUsat-1	1U	RFMD RF2905	437.475	Amateur	400 mW	AX.25	2400 FSK [1]	Canted Turnstyle
	CanX-1	1U	Melexis	437.880	Amateur	500 mW	Custom	1200 MSK [1]	Crossed Dipoles
✓	Cute-1 CO-55	1U	Maki Denki (Beacon) Alinco DJ-C4 (Data)	436.8375 437.470	Amateur	100 mW 350 mW	CW AX.25	50 WPM 1200 AFSK	Monopole Monopole
	QuakeSat-1	3U	Tekk KS-960	436.675	Amateur	2 watts	AX.25 (Pacsat)	9600 FSK	Turnstyle
✓	XI-IV CO-57	1U	Nishi RF Lab (Beacon) Nishi RF Lab (Data)	436.8475 437.490	Amateur	80 mW 1 watt	CW AX.25	50 WPM 1200 AFSK	Dipole Dipole
✓	XI-V CO-58	1U	Nishi RF Lab (Beacon) Nishi RF Lab (Data)	437.465 437.345	Amateur	80 mW 1 watt	CW AX.25	50 WPM 1200 AFSK	Dipole Dipole
	NCube-2 [2]	1U		437.505	Amateur		AX.25	1200 AFSK [1]	Monopole
	UWE-1	1U	PR-430	437.505	Amateur	1 watt	AX.25	1200/9600 AFSK	End-Fed Dipole
✓	Cute-1.7+APD I CO-56	2U	Alinco DJ-C5 (Telemetry)	437.385 437.505	Amateur	100 mW 300 mW	CW AX.25/SRLL	50 WPM 1200 AFSK/9600 GMSK	Dipole Dipole
	GeneSat-1	3U	Atmel ATA8402 (Beacon) Microhard MHX-2400	437.067 2.4 GHz	Amateur	500 mW 1 watt	AX.25 Proprietary	1200 AFSK	Monopole Patch
	CSTB1	1U	Commercial [4]	400.0375	Experimental	<1 watt	Proprietary	1200 AFSK	Dipole
	AeroCube-2	1U	Commercial [4]	902-928	ISM	2 watts	Proprietary	38.4 K	Patch
	CP4	1U	TI CC1000	437.325	Amateur	1 watt	AX.25	1200 FSK	Dipole
	Libertad-1	1U	Stensat	437.405	Amateur	400 mW	AX.25	1200 AFSK	Monopole
	CAPE1	1U	TI CC1020	435.245	Amateur	1 watt	AX.25	9600 FSK	Dipole
✓	CP3	1U	TI CC1000	436.845	Experimental	1 watt	AX.25	1200 FSK	Dipole
	MAST	3U	Microhard MHX-2400	2.4 GHz	ISM	1 watt	Proprietary	15 Kbps	Monopole
✓	Delfi-C3 DO-64	3U	Custom Beacon Custom Transponder	145.870 145.9/435.55	Amateur	400 mW 200 mW	AX.25 Linear XPNDR	1200 BPSK 40 KHz BW	Turnstyle Turnstyle
✓	SEEDS-2 CO-66	1U	Mushashino (Beacon) Mushashino (Data)	437.485 437.485	Amateur	90 mW 450 mW	CW AX.25	1200 AFSK	Monopole Monopole
✓	CanX-2	3U	Custom S-band	2.2 GHz	Space Research	500 mW	NSP	16-256 Kbps BPSK	Patch
✓	AAUSAT-II	1U	Holger Eckhardt DF2FQ	437.425	Amateur	610 mW	AX.25	1200 MSK	Dipole
✓	Cute-1.7+APD II [3] CO-65	3U	Invax (Beacon) Alinco DJ-C5 (Data)	437.275 437.475	Amateur	100 mW 300 mW	CW AX.25/SRLL	50 WPM 1200 AFSK/9600 GMSK	Monopole Monopole
✓	Compass-1	1U	BC549 (Beacon) Holger Eckhardt (Data)	437.275 437.405	Amateur	200 mW 300 mW	CW AX.25	15 WPM 1200 AFSK/MSK	Dipole Dipole

1. Satellite was never heard from when in space.
2. This object separated from SSETI Express months later and is presumed to be NCube-2.
3. This satellite is larger than a CubeSat spaceframe but design is based upon earlier CubeSat designs.
4. Manufacturer and model unknown.