A Survey of CubeSat Communication Systems: 2009–2012

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Abstract

This paper is a short survey of the communication subsystems of CubeSats successfully launched into orbit between the Minotaur 1 launch in May 2009 and the ELaNa-6/NROL-36 launch in September 2012. Detailed information about the radios, data rates, antennas, and ground stations is included. The transition from amateur satellite service to experimental service for US CubeSats is discussed. We make recommendations to increase the chance of communications success.

Contents

1 Introduction

This paper is an update to an earlier survey of CubeSat Communications [1]. The current paper surveys the communications subsystems on CubeSats launched from May 2009 to September 2012, clearly showing that the communication system is one major limiting factor for CubeSats.

Chapter 2 describes some of the licensing requirements for CubeSats built by US developers. Chapter 3 provides recommendations for new and existing CubeSat teams to increase their chances of a successful project. Chapter 4 is a condensed table of all the CubeSats described in Chapter 5 of this paper, which details the communication subsystems of the 49 CubeSats launched from May 2009 to September 2012.

2 United States Licensing Requirements

As identified in 2002 [2, 3], spectrum licensing takes the longest amount of time for CubeSat communications, often longer than building and testing the satellite. Until 2011, the Federal Communications Commission (FCC) was content to let CubeSats use the amateur satellite service, even if they didn't follow all of the amateur radio regulations in Part 97.

The CubeSat licensing issue was brought to the forefront during the launch of ELaNa-3/NPP in October 2011. For a variety of reasons, the FCC did not file the correct international notification paperwork with the International Telecommunications Union (ITU) for the CubeSats on this launch. Several days before launch, the ITU notified the FCC about this. The CubeSat teams scrambled to fill out all the paperwork, and all documents were submitted to the ITU before launch [5].

Due to this mix-up, the FCC became more active at the CubeSat Summer Workshop during the Small Satellite Conference in Logan, Utah, in August 2012. A representative from the FCC suggested that most CubeSat teams should get an experimental license instead of amateur, based on Section 97.113, which prohibits any type of payment to the licensee or control operators of the spacecraft [4].

FCC met in November 2012 with representatives from NASA, NRO, and the CubeSat community to prevent this licensing issue in the future. The results of this meeting are contained in FCC Public Notice DA-13-445A1, "Guidance on Obtaining Licenses for Small Satellites." This document touches on who is eligible to apply for a license, how to apply, what documents are required, orbital debris mitigation, and post-launch notifications.

Figure 1 shows a flow diagram, based on this FCC Public Notice and communication with FCC employees, for determining which license CubeSat teams should apply for. These documents and charts reflect one interpretation of the views of the FCC, and are not applicable to US Government-funded and -operated satellites (licensed by the NTIA) or to international CubeSats.

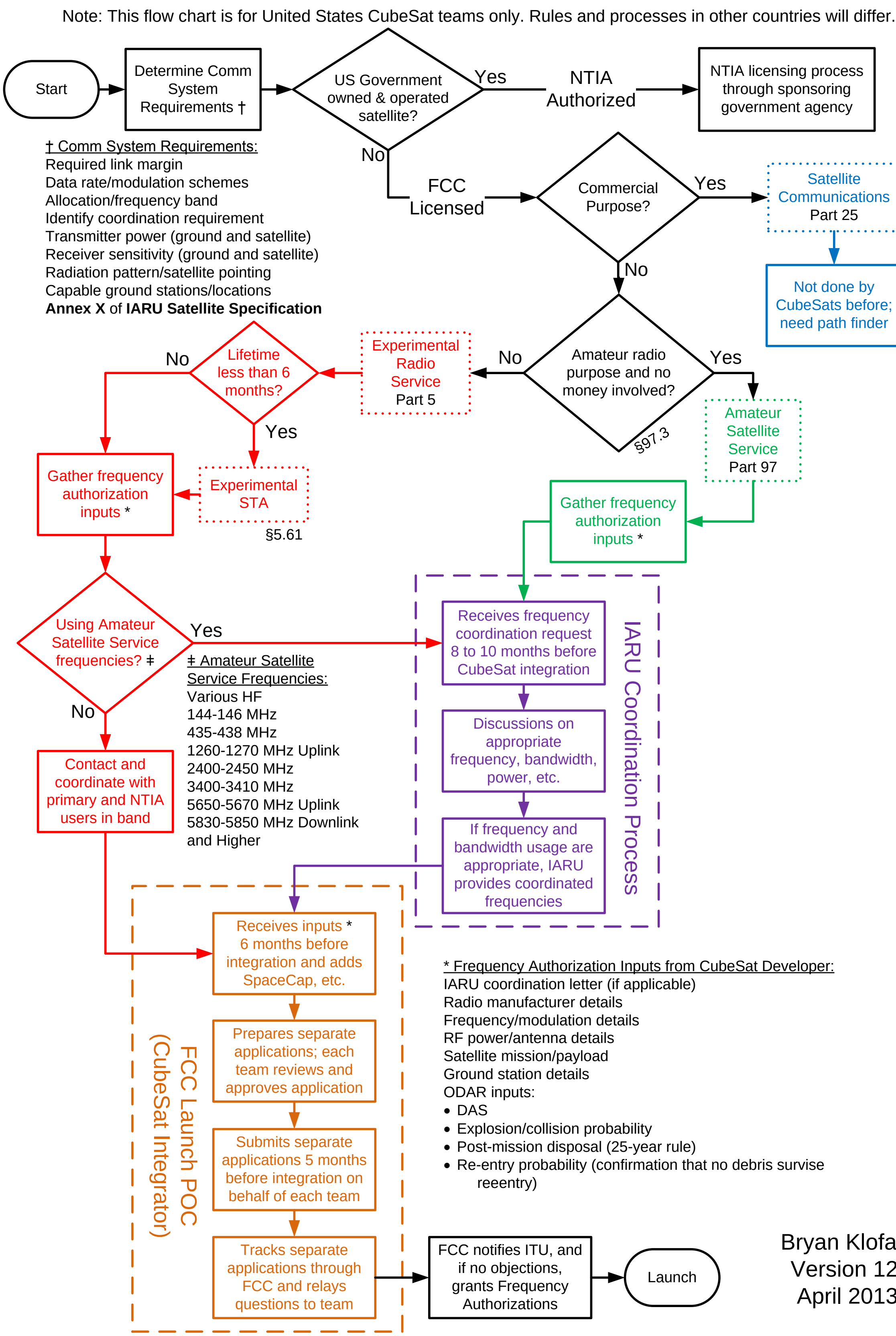


Figure 1: United States licensing flow chart.

3 Recommendations

Based on the the research for this paper, we have several recommendations for CubeSat developers with respect to their communications subsystem. Our earlier recommendations are still valid [1].

Timeframe: Teams should begin thinking about frequency licensing of their satellites when the project starts, even before any hardware has been designed or purchased. For non-government teams in the US, the FCC is encouraging an experimental license, with IARU coordination letter if applicable (see previous section). Licensing often takes one year or more.

Command Receivers: Never turn off command receivers for any reason. Several satellites power budgets had so little margin that teams turned off the command receivers to save power, instituting an orbit propagation algorithm to turn on the receiver when the satellite thinks it's above the primary ground station. However, the orbit predictor sometimes has the wrong inputs or the satellite gets put into the wrong orbit, so the command receiver is off over the primary ground station. If the power budget margin for your spacecraft is this thin, consider rethinking the entire power approach. Remember that all satellite transmitters must be actively controlled, and must be commanded off if interference is generated for the primary users.

Scheduled Downlinks: If permissible by the type of license, small satellites should be able to schedule data downlinks. This is helpful for downlinking over receive-only stations that may be far away from the primary ground station. RAX-2 successfully used scheduled downlinks to downlink data to ground receivers in New Zealand, California, and Florida.

CubeSat Radios: While CubeSat developers on a budget might question the value of buying a COTS radio designed for CubeSats, these radios have already performed well on previous missions. For teams that aren't interested in building their own radios, COTS CubeSat radios are flight-qualified, have well-defined interfaces, and generally provide good value for the price. Companies that make these COTS CubeSat radios include AstroDev, ISIS, and Stensat.

Systems Engineering: The radio is only one small part of the satellite system. Is the over-the-air data rate high enough to fulfill the requirements? Is there enough power for long-duration or high-power transmission? Are there enough capable ground stations to receive the signals? Is the interface between the radio and main processor robust enough to sustain the high data rates required? Is the data rate high enough between the spacecraft memory and main processor? These questions can be answered with a bit of systems engineering.

It is our hope that these recommendations help new and established CubeSat teams, because there is no point in launching a CubeSat that can't be communicated with.

4 Satellite Comparison

The table below, grouped by launch campaign, shows a summary of the communications subsystems of the satellites. Each line is a different physical radio. Only downlink frequencies are listed. Blank cells indicate the information not known as of April 2013.

- **Object** refers to the spacecraft ID number in the NORAD database, available at www.space-track.org, although some of the launches for sensitive primary satellites do not have keps posted. Refer to the sponsoring organization's web page.

- An integrated **TNC** (terminal node controller) means that the radio module accepts serial data and uses an internal processor to format the data.
- For **Rate/Modulation**, remember that the symbol rate (baud) is not necessarily the same as the 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 (beacons transmit continuously).
- **Lifetime** refers to the length of the useful life of the satellite.
- **Status** refers to it's current status in April 2013:
  - **Deorbited:** The spacecraft has deorbited.
  - **DOA:** Dead on Arrival. This satellite was never heard from in space.
  - **Dead:** Spacecraft is now no longer transmitting.
  - **Alive:** Satellite is beaconing data, but not achieving its mission, or the mission has ended.
  - **Active:** CubeSat is performing its intended mission.

Table 1: Summary of Spacecraft Transmitters.

Satellite	Object	Size	Radio	Frequency	Satellite Service	Power	TNC	Protocol	Baud Rate/Modulation	Downloaded	Lifetime	Antenna	Status
Minotaur 1; 19 May 2009													
AeroCube-3	35005	1U	Freewave FGRM	915 MHz	experimental	2 W	Integrated	Proprietary	77 kbaud GFSK	52 MB	7 months	patch	Deorbited
CP6	35003	1U	CC1000/RF2117	437.365 MHz	amateur	1 W	PIC18LF6720	AX.25	1200 baud FSK		4 months	dipole	Dead
HawkSat-1	35004	1U	Microhard MHX-425	437.345 MHz	amateur	1 W	Integrated	Proprietary		0 kB	0 days	monopole	DOA
PharmaSat	35002	3U	Microhard MHX-2400	2.4 GHz	experimental	1 W	Integrated	Proprietary	10 kbps	650 kB	10 days	patch	Dead
			Stensat (beacon)	437.465 MHz	amateur	500 mW	Integrated	AX.25	1200 baud AFSK	N/A	1 month	monopole	
ISILaunch 01/PSLV-C14; 23 Sep 2009													
BEESAT-1	35933	1U		436.000 MHz	amateur[1]	500 mW	CMX909B	Mobitex	4800/9600 baud GMSK		43+ months	monopole	Alive
UWE-2	35934	1U	PR430	437.385 MHz	amateur	1 W	Internal	AX.25	1200 baud AFSK		1 week	dipole	Dead
ITUpSAT-1	35935	1U	Microhard MHX-425	437.325 MHz	amateur	1 W	Integrated	Proprietary	19200 baud	0 kB[2]	43+ months	dipole	Alive
			BeeLine/CC1050	437.325 MHz	amateur	350 mW		CW		N/A		monopole	
SwissCube	35932	1U	Butler oscillator/RF5110G	437.505 MHz	amateur	1 W	MSP430F1611	AX.25	1200 baud FSK	0 kB	43+ months	monopole	Active
			RF2516 (beacon)	437.505 MHz	amateur	100 mW	Integrated	CW	10 WPM	N/A		monopole	
H-IIA F17; 20 May 2010													
Hayato	36573	1U	Custom	13.275 GHz	Earth exploration	100 mW	Integrated		10 kbps/1 Mbps BPSK	0 kB[2]	18 days	patch	Deorbited
Waseda-SAT2	36574	1U	TXE430-301A	437.485 MHz	amateur	150 mW	H8/3052F[3]	AX.25	9600 baud FSK	0 kB	0 days	monopole	DOA
			TXE430-301A (beacon)	437.485 MHz	amateur	100 mW	H8/3052F[3]	CW		N/A		dipole	Deorbited
Negai-Star	36575	1U	Data	437.305 MHz	amateur	150 mW		AX.25	1200 baud FSK		1 month	dipole	Deorbited
			Beacon Radio	437.305 MHz	amateur	100 mW		CW	50 WPM	N/A		dipole	
NLS-6/PSLV-C15; 12 July 2010													
TIsat-1	36799	1U	Alinco DJ-C6	437.305 MHz	amateur	500 mW	MSP430F169	AX.25	1200 baud AFSK		33+ months	monopole	Active
			CC1010 (beacon)	437.305 MHz	amateur	400 mW	MSP430F169	CW	15-110 WPM	N/A		monopole	
StudSat	36796	1U	CC1020	437.505 MHz	amateur	500 mW	UC3A0512[3]	Custom AX.25	4800 baud FSK	0 kB[2]	5 days	monopole	Dead
			MAX1472 (beacon)	437.860 MHz	amateur	10 mW	UC3A0512[3]	CW	22 WPM	N/A		monopole	
STP-S26; 19 Nov 2010													
RAX-1	37223	3U	Lithium-1	437.505 MHz	amateur	750 mW	Integrated	AX.25	9600 baud GMSK	4.8 MB	2 months	turnstile	Dead
O/OREOS	37224	3U	Microhard MHX-2400	2.4 GHz	experimental	1 W	Integrated	Proprietary	Variable	8 MB	29+ months	patch	Alive
			Stensat (beacon)	437.305 MHz	amateur	500 mW	Integrated	AX.25	1200 baud AFSK	N/A		monopole	
NanoSail-D2	37361	3U	Microhard MHX-2400	2.4 GHz	experimental	1 W	Integrated	Proprietary	Variable		5 days[4]	patch	Deorbited
			Stensat (beacon)	437.270 MHz	amateur	500 mW	Integrated	AX.25	1200 baud AFSK	N/A		monopole	
Falcon 9-002; 8 Dec 2010													
Perseus (4)	37251	1.5U			government						1 month		Deorbited
QbX (2)	37249	3U	TTC	450 MHz	government	1 W			9600 baud GMSK		1 month	quadrafilar helix	Deorbited
SMDC-ONE	37246	3U	Pericle	UHF	government						1 month	turnstile	Deorbited
Mayflower	37252	3U	Microhard MHX-425	437.000 MHz	unlicensed	1 W	Integrated	Proprietary	Variable	0 kB[2]	2 days	dipole	Deorbited
			Stensat (beacon)	437.600 MHz	unlicensed	1 W	Integrated	AX.25	1200 baud AFSK	N/A			

[1] This satellite was not coordinated through the IARU.

[2] Uplink commands were never received by this satellite.

[3] This is also the main spacecraft processor.

[4] There were no solar cells on this satellite.

Table 2: Summary of Spacecraft Transmitters (Continued).

Satellite	Object	Size	Radio	Frequency	Satellite Service	Power	TNC	Protocol	Baud Rate/Modulation	Downloaded	Lifetime	Antenna	Status
PSLV-C18; 12 Oct 2011													
Jugnu	37839	3U	CC1070/RF5110G	437.505 MHz	amateur	1 W		AX.25	2400 baud FSK		18+ months	monopole	Alive
			MAX1472 (beacon)	437.505 MHz	amateur	10 mW		CW	20 WPM	N/A		monopole	
ELaNa-3/NPP; 28 Oct 2011													
AubieSat-1	37854	1U	Melexis TH72011	437.475 MHz	amateur	800 mW	ATmega1281[1]	CW	20 WPM	0 kB	18+ months	dipole	Alive
DICE (2)	37851	1.5U	L3 Cadet	465 MHz	meteorological	1 W	Integrated	Proprietary	2.6 Mbps BPSK	8.4 GB	18+ months	dipole	Active
HRBE	37855	1U	CC1000	437.505 MHz	amateur	850 mW		AX.25	1200 baud FSK	7.6 MB	18+ months	monopole	Active
M-Cubed	37855	1U	Lithium-1	437.485 MHz	amateur	1 W	Integrated	AX.25	1200 baud FSK	0 kB[2]	18+ months	monopole	Alive
RAX-2	37853	3U	Lithium-1	437.345 MHz	amateur	1 W	Integrated	AX.25	9600 baud GMSK	242 MB	18+ months	turnstile	Active
Vega VV01; 13 Feb 2012													
Xatcobeo	38082	1U	GomSpace U482C	437.365 MHz	amateur	500 mW	Integrated	AX.25/CW	1200 baud MSK/20 WPM		14+ months	turnstile	Active
ROBUSTA		1U	MC12181/MAX2608	437.325 MHz	amateur	800 mW	PIC18F4580[1]	AX.25	1200 baud AFSK	0 kB[3]	2 days	dipole	Dead
e-st@r	38079	1U	BHX2-437-5	437.445 MHz	amateur	500 mW	PIC16	AX.25	1200 baud AFSK	0 kB[2]	3 days	dipole	Dead
Goliat	38085	1U	Alinco DJ-C7	437.485 MHz	amateur	500 mW	FX614/MSP430	AX.25/CW	1200 baud AFSK/20 WPM		1 week	monopole	Dead
			Microhard MHX-2420	2.4 GHz		1 W	Integrated	Proprietary	Variable	0 kB[3]		patch	
PW-Sat	38083	1U	ISIS TRXUV	145.900 MHz	amateur	200 mW	Integrated	AX.25/CW	1200 baud BPSK/12 WPM		10 months	dipole	Dead
Masat-1	38081	1U	Si4432	437.345 MHz	amateur	100/400 mW	dsPIC33F[1]	Custom/CW	GFSK/120 CPM	305 MB	14+ months	monopole	Active
UniCubeSat-GG		1U	AstroDev Custom	437.305 MHz	amateur	500 mW	Integrated	AX.25/CW	9600 baud GFSK	0 kB[2]	2 days	dipole	Dead
ELaNa-6/NROL-36; 13 Sep 2012													
SMDC-ONE (2)	38766	3U	Pericle	UHF	government							turnstile	Alive
AeroCube-4 (3)	38767	1U	FreeWave MM2	915 MHz	experimental	2 W	Integrated	Proprietary	38.4 kbaud		8+ months	patch	Active
			CC1101	915 MHz	experimental	1.3 W	Integrated	Proprietary	500 kbps FSK			patch	
Aeneas	38760	3U	MHX-425	437.000 MHz	experimental	1 W	Integrated	Proprietary	Variable		8+ months	monopole	Alive
			Stensat (beacon)	437.600 MHz	amateur	1 W	Integrated	AX.25	1200 baud FSK	N/A	8+ months	monopole	
CSSWE	38761	3U	Lithium-1	437.345 MHz	experimental	1 W	Integrated	AX.25	9600 baud GFSK	60 MB	8+ months	monopole	Active
CP5	38763	1U	CC1000/RF2117	437.405 MHz	amateur	500 mW	PIC18LF6720	AX.25	1200 baud FSK	500 kB	4 months	dipole	Dead
CXBN	38762	2U	Lithium-1	437.525 MHz	amateur	1 W	Integrated	AX.25	9600 baud GFSK		8+ months	turnstile	Active
CINEMA	38764	3U	Emhiser	2200 MHz	space research	1 W	FPGA	Proprietary	1 Mbps FSK		8+ months	patch	Active
Re	38765	3U	Helium-100	915 MHz	government	1 W	Integrated	AX.25	57.6 kbps FSK			dipole	

[1] This is also the main satellite processor.

[2] Uplink commands were never received by this satellite.

[3] This spacecraft did receive uplink commands, but it died before before downlink could be established.

5 Satellite Detail

The following sections discuss each CubeSat launched from May 2009 to September 2012, in chronological order grouped by launch campaign.

5.1 Minotaur-1

This Minotaur-1 rocket went into space from Wallops Flight Facility on 19 May 2009, with TacSat-3 as the primary payload. The CubeSat Technology Demonstration Mission was coordinated by the Hawk Institute for Space Sciences in Virginia. One Cal Poly Mk. III P-POD contained three 1U CubeSats, and another NASA-modified Mk. II P-POD contained PharmaSat. These satellites were placed in a low orbit, around 450-km circular, and all of the satellites have deorbited [6].

Figure 2: Aerocube-3, CP6, and HawkSat-1 before integration in Maryland [6].

5.1.1 AeroCube-3

AeroCube-3 was the third CubeSat from The Aerospace Corporation, building on the experiences with AeroCube-2. Several payloads were on board, including several imagers and a deorbit balloon. The spacecraft was tethered to the upper stage of the Minotaur rocket and deployed as the satellite came out of the P-POD. However, it is theorized that the tether came in contact with the still glowing-hot motor and severed within minutes of deployment. The deorbit balloon deployed but did not inflate, but still drastically reduced the amount of time the spacecraft was in orbit [7].

AeroCube-3 contained a communications subsystem similar to the previous AeroCube satellites, consisting of a Freewave Technologies frequency-hopping 915 MHz ISM radio. Modification for flight included locking the radio on a single channel, extending the doppler range, and modifying link delay parameters. The antenna consisted of a surface-mounted patch antenna.

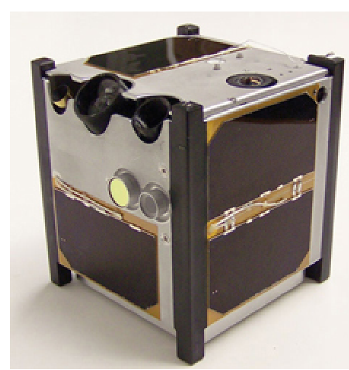


Figure 3: AeroCube-3 [7].

A 16-ft dish at The Aerospace Corporation in El Segundo, California, was the primary ground station, with a secondary 6-ft dish in Hawaii [8]. Terrestrial noise in Los Angeles was a problem for low-elevation passes. The Aerospace Corporation downloaded around 52 MB of data to the ground[9].

AeroCube-3 also used a novel method for affixing the solar cells to the spacecraft. Instead of using the usual silicone RTV method, double-sided kapton tape was used. Infrared thermography inspection showed fewer voids behind the solar cells than with traditional methods [10]. AeroCube-3 deorbited on 6 January 2011.

5.1.2 CP6

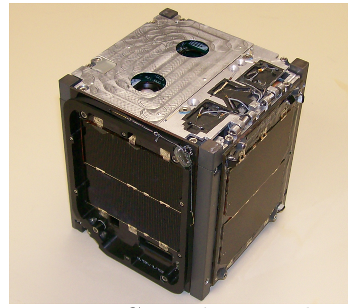


Figure 4: CP6, showing the deployable top panel [11].

Built by California Polytechnic State University (Cal Poly), CP6 started life as a flight backup for CP3, and included minor bus upgrades to help fix problems found in the earlier spacecraft. CP6 carried two payloads: the same imagers as CP3, and a new plasma experiment from the Naval Research Laboratory that fit in the 25-mm of unused space above the imagers. This electron-collector experiment consisted of three deployable steel tapes, each longer than 1-meter. The emitter tape contained a tungsten filament at the tip, which thermionically ejected electrons into the plasma. The two other tapes collected electrons from the surrounding plasma [11].

As had the earlier satellites, CP6 contained two Texas Instruments CC1000 FSK transceivers. Based on lessons learned from previous flights of this bus, a preamplifier and filter were added to the receivers [12]. These modifications seemed to help the satellite successfully decode uplink commands during the middle of passes, but the receiver performance was still short of expectations.

CP6 mysteriously died four months after launch. None of the payloads, including the cameras or NRL plasma experiment, were exercised before failure. CP6 deorbited on 6 October 2011.

5.1.3 HawkSat-1


Figure 5: Hawksat-1 [13].

The Hawk Institute for Space Sciences built this 1U CubeSat with a radiation test payload for a major aerospace firm. It was the first CubeSat entirely designed, built, and flown from Maryland's eastern shore. It was built as a test satellite to show that a complete satellite could be built and integrated in Maryland [6].

This satellite was built around a 1U Pumpkin structure and FM430 processor board. The power system was a Clyde Space EPS board with two battery modules. This bus occupied 8.9 cm and 840 grams of the 1U spacecraft [13].

HawkSat-1 contained a Microhard MHX-425, licensed in the amateur satellite service. Due to high DC receive current, this radio checked for a signal from the ground only every 30 seconds, then turned off. Doppler frequency shift was initially not accounted for in the link, and was hastily accounted for after launch, but never tested. Due to the lack of doppler compensation and handshaking requirements, HawkSat-1 was never heard from in space. It deorbited on 4 September 2011 [14].

5.1.4 PharmaSat

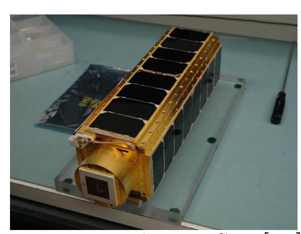


Figure 6: PharmaSat [16].

Following with the same bus and with a mission similar to GeneSat-1, PharmaSat contained 48 microwells for growing yeast and measuring the efficiency of anti-fungal compounds. This was a continuation of the experiments done by GeneSat-1 in December 2006 [15].

The communications subsystem for this spacecraft was almost identical to that of GeneSat-1. The primary command transceiver consisted of a Microhard MHX-2400 radio, and this spacecraft also contained a UHF beacon. While the MHX-2400 was capable of higher data rates, the serial speed between Microhard and the main processor was only 9600 baud, effectively limiting the maximum over-the-air data rate to less than 9600 baud. The actual over-the-air data rate for most passes was less than 800 bps. The ground segment consisted of an 18-meter dish at SRI International, and smaller, dual 3-meter dishes at Santa Clara University, where students performed flight operations for PharmaSat.

PharmaSat failed after eight days in orbit, a few passes after the science team declared the mission a success. The failure was caused by a miscommunication in the data path between the Microhard MHX-2400 radio and the main processor on board. A power reset would have cleared the error, but that capability was not built into the bus [17]. PharmaSat deorbited on 14 August 2012.

5.2 ISILaunch 01/PSLV-C14

This was the first launch coordinated by Innovative Solutions in Space (ISIS), a small company based in Delft, The Netherlands. ISIS was born from the Delfi-C3 project. This PSLV-C14 blasted off on 23 September 2009 from Sriharikota, India, with Oceansat-2 as the primary payload. The satellites went into a 720-km near-circular orbit at 98.2°.

These CubeSats deployed from four 1U Single Picosatellite Deployers (SPLs), built by Astro und Feinwerktechnik Adlershof GmbH in Germany. This spring-loaded system uses permanent magnets as the actuators [19].

All CubeSats on this launch contained a low-power CW beacon, which made it easy for ground stations to determine which Keplerian elements corresponded to which satellite.

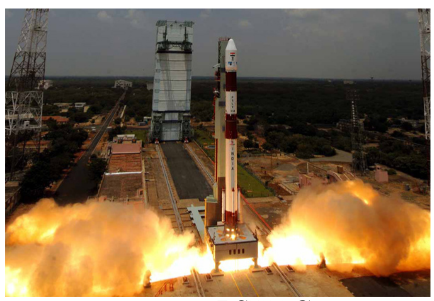


Figure 7: PSLV C14.

5.2.1 BEESAT-1

The first CubeSat built by Technical University of Berlin, Berlin Experimental and Educational Satellite is a technology demonstration mission to test new micro reaction wheels developed at the university. It also contains a small camera.

The main processor is an NXP LPC2292 running at 60 MHz, with 2 MB of RAM and 20 MB of flash memory [20].

BEESAT-1 transmits 4800 or 9600 baud GMSK signals at 435.950 MHz. The power output is 500 mW into a monopole antenna. It uses a Mobitex packet format, with forward error correction, from a Consumer Microcircuits Limited CMX909B TNC. This satellite is licensed under the amateur satellite service, but it does not seem to have been coordinated through the IARU [21]. BEESAT-1 is still active over the primary ground station in Berlin.

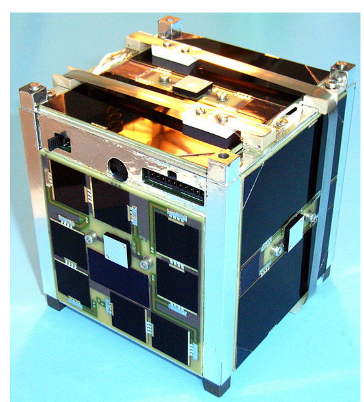


Figure 8: BeeSat-1 [21].

5.2.2 UWE-2

Built by students at the University of Wuerzburg, the University of Wuerzberg Experimental-2 CubeSat was an evolutionary step from their earlier UWE-1 CubeSat launch on SSETI Express. This 1U's main experiment was precise attitude determination by combining and filtering data from the on-board accelerometer, three miniature gyroscopes, Phoenix GPS receiver, and six sun sensors [22].

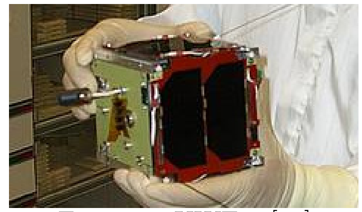


Figure 9: UWE-2 [22].

The main processor was a Hitachi H8S running uClinux. The communications system was the same as their earlier CubeSat, based around a slightly-modified SR-Systems PR430. It transmitted AX.25-formatted data at 1200 baud AFSK on 437.385 MHz with 1 watt of output power. The antenna was a dipole. UWE-2 ceased functioning in October 2009 [23].

5.2.3 ITUpSAT1

ITUpSAT1 was built by students at Istanbul Technical University. The primary purpose is student education, and the main payload is a VGA camera based on an OV7620 image sensor. The other secondary payloads included a three-axis accelerometer, gyro, and magnetometer.

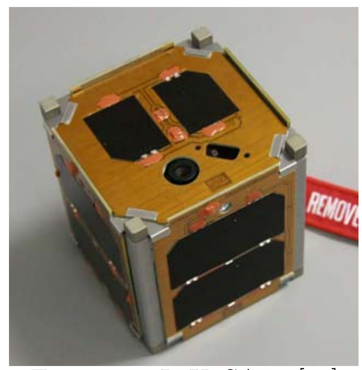


Figure 10: ITUpSAT1 [24].

The satellite is a standard Rev D CubeSat Kit from Pumpkin Inc., with the MSP430 main processor and Clyde Space EPS with lithium polymer batteries. Attitude is controlled with a passive magnetic system [24].

The primary transceiver is a Microhard MHX-425, transmitting 1 W into a dipole antenna. On the first pass of the satellite over the university ground station, a link was temporarily established with the MHX-425 radio, but no data was transferred. The Microhard has not been communicated with since. The beacon is a BeeLine module, a small 100 mW CW transmitter based on a CC1050 single-chip transmitter. Power is boosted to 350 mW via a custom-built amplifier. While this beacon was designed for model rockets, it has operated for 3.5 years. The beacon uses a monopole antenna [25].

5.2.4 SwissCube

SwissCube was built by a consortium of universities in Switzerland, including the Federal Institute of Technology of Lausanne (EPFL). The primary mission of this spacecraft is student education, and the scientific payload includes a 45 mm telescope for measuring airglow. This spacecraft also contains a three-axis magnetometer, three single-axis gyroscopes, and six novel MEMS sun sensors [26].

Figure 11: SwissCube [26].

The structure was built using a wire electrical discharge machining (EDM) process, which removes all the internal material from a single block of aluminum, for a total mass of 95 grams [27]. The power system was built by students, and directly powers the beacon board, which transmits a 10 WPM CW signal at 100 mW from an RF Microdevices RF2516 modulator and a RF2172 power amplifier. This separate beacon system was done to ensure that even if the rest of the satellite failed, the beacon would still operate and send limited telemetry to the ground.

The main transmitter operates in the amateur satellite service at 437.505 MHz. The MSP430F1611 TNC directly modulates a discrete butler oscillator, and an RF Microdevices RF5110G amplifies the signal to slightly less than 1 watt [28]. The modulation scheme is 1200 bps FSK with AX.25 packet formatting. Antennas are quarter-wave monopoles for each frequency, with a nichrome burn wire for deployment [29].

For an unknown reason, SwissCube came out of the SPL spinning very fast, around 200°/sec. Due to an I2C bus error, the team couldn't turn on the ADCS system. SwissCube was left to detumble by itself until January 2011, when the rate was reduced to 80°/sec. The team was then able to command on the power amplifier for an extended period of time, draining the batteries and resetting the satellite. The I2C bus problem cleared itself, and science operations, which began shortly thereafter, were a complete success [30].

5.3 H-IIA F17

This rocket blasted off on 20 May 2010 with the Akatsuki probe, also known as the Venus Climate Orbiter (VCO), as the primary payload. After deploying the CubeSats between the first and second burns of the second stage, the rocket headed toward Venus with the primary satellite and UNITEC-1, a 15-kg satellite from a consortium of 20 Japanese universities. UNITEC-1 used the 5.8 GHz amateur band for communications, but the satellite became silent a few weeks after launch.

These three CubeSats were deployed into a very low 292- x 306-km orbit at 30° from two JAXA Picosatellite Deployers (J-PODs), one with Hayato and Negai-Star, and the other with Waseda-SAT2 [31].

Figure 12: H-IIA F17 on the pad.

5.3.1 Hayato

Built by Kagoshima University and called K-Sat before launch, the mission of this 1U CubeSat was to observe atmospheric moisture content to predict heavy localized rains. It also contained a camera for taking pictures of the earth. The spacecraft was gravity-gradient stabilized with a 60 cm fold-out boom [32].

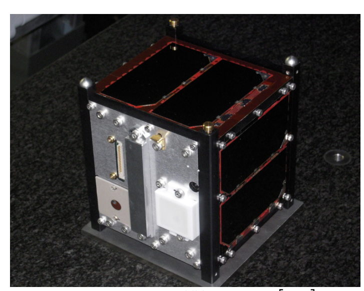


Figure 13: Hayato [32].

The main processor was a PIC16F877A running at 4 MHz. Power was supplied by sixteen AAA-sized Ni-MH batteries and triple-junction solar cells. Attitude determination and control was provided by another PIC16F877A with a AMI302 mag sensor.

This satellite used a 100 mW Ku-band 13.275 GHz transmitter in the Earth-exploration satellite service with a data rate of 10 kbps or 1 Mbps, depending on the mode [33]. Uplink to Hayato was never achieved, so the satellite was just beaconing housekeeping data at the slower data rate for it's entire 18 day life. Hayato decayed on 14 July 2010 [34, 35].

5.3.2 Waseda-SAT2

Built by students from Waseda University in Japan, this 1U CubeSat's mission investigated whether fold-out solar panels can stabilize the attitude of the satellite. It also contained an educational optical experiment, with LEDs displaying a QR code that contained satellite telemetry. An on-board camera downlinked pictures of the QR code, as well as general pictures of the earth [36].

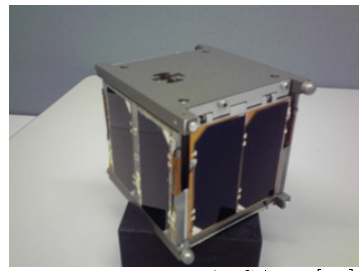


Figure 14: Waseda-SAT2 [36].

The communications system was built around two TXE430-301A transmitter from Nishi Musen Kenkyusyo Co. Both transmitted on 437.485MHz, one a 100 mW CW beacon and the other a 150 mW high-speed 9600 baud FSK downlink. This satellite was never heard from in space. Waseda-SAT2 decayed on 12 July 2010 [37].

5.3.3 Negai-Star

This 1U CubeSat was built by students at Soka University in Japan. Its primary mission was to flight-test a commercial FPGA.

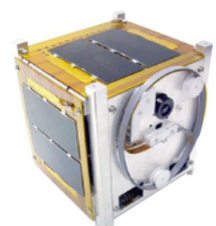


Figure 15: Negai-Star [38].

Negai-Star contained two transmitters. The beacon transmitted a 100 mW CW signal at 50 WPM. The data downlink was a 1200 baud AFSK transmitter with 400 mW of output power and AX.25 framing. Both transmitters were on 437.305 MHz under the amateur satellite service, and the UHF downlink antenna was a dipole. This satellite deorbited on 26 June 2010 [38].

5.4 NLS-6/PSLV-C15

The primary vehicle on this mission was Cartosat-2B, a remote sensing satellite built by the Indian Space Research Organization (ISRO). This launch also contained several secondary satellites, including AlSat-2A and AISSat-1, a 20-cm nanosatellite that tracks ships via their AIS signals. This rocket blasted off on 12 July 2010 into a 630-km circular orbit at 98° [39].

The University of Toronto Institute for Aerospace Studies' Space Flight Laboratory provided launch services for AISSat-1 and TIsat-1 through their Nanosatellite Launch Service (NLS-6) program. TIsat-1 was deployed from a single 1U X-POD. StudSat was released from a deployer built by ISRO.

Figure 16: PSLV-C15 [39].

5.4.1 TIsat-1

TIsat-1 is a 1U CubeSat built by the University of Applied Sciences of Southern Switzerland, with the primary purpose of student education. The payload measures atomic oxygen effects on exposed thin bonding wires and nylon wires. It is also designed to be extremely fault-tolerant with three main processors [40].

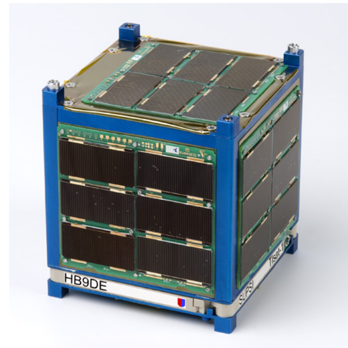


Figure 17: TIsat-1 [40].

TIsat-1's structure was designed and built by students in collaboration with RUAG Aviation in Lodrino. The power system was custom-built and contained both single lithium-ion and single lithium-polymer batteries. TIsat-1 contains three main processors: one MSP430F169, one PIC18LF8722, and one PIC16.

This 1U CubeSat contains a custom-designed beacon transmitter and an Alinco DJ-C6 transceiver transmitting 500 mW. Both radios operate on 437.305 MHz, and use the main satellite processor as the TNC. The CW beacon is based on a CC1010 with a Motorola power amplifier, and transmits 400 mW of power with a symbol rate of 15 WPM, gradually increasing to 180 WPM over a ten-day period. The satellite contains two monopole antennas for uplink and downlink [41]. TIsat-1 is still operating today.

5.4.2 StudSat

An abbreviation for Student Satellite, this 1U CubeSat was the first satellite built entirely by students in a consortium of seven engineering colleges in India. Its primary mission was student education and promotion of space technology in educational institutions. StudSat contained a visible CMOS imager with a ground resolution of 90 meters, and had a mass of around 650 grams [42].

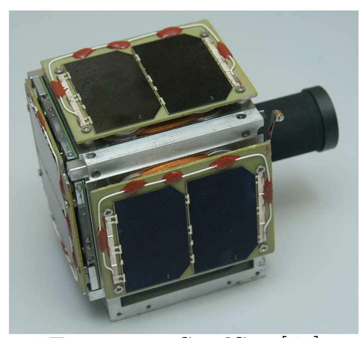


Figure 18: StudSat [42].

The primary microcrontroller on board was an Atmel 32-bit UC3A0512, and the power system was from Clyde Space. This power system had a fatal flaw caused by a faulty DC downconverter, and it is theorized that this caused the spacecraft to fail after several days of operation.

The data downlink radio was based on a CC1020 transmitter at 437.505 MHz under an amateur license. The power output was about 500 mW, and the data rate was 4800 baud FSK with a custom AX.25 protocol with the main processor acting as the TNC. The satellite also contained a morse code beacon on 437.860 MHz based on a MAX1472 crystal-based ASK transmitter chip. It transmitted 10 mW at 22 WPM with a two-minute period. Beacons were received by various amateur radio operators around the world [43].

The satellite contained an orbit propagator that turned on the spacecraft receiver only when the satellite was above the primary ground station at the Nitte Meenakshi Institute of Technology in Bangalore. However, the spacecraft was not put exactly in the orbit that was specified in the propagator, so the receiver was not active over the primary ground station and no uplink commands were ever received by the spacecraft [44].

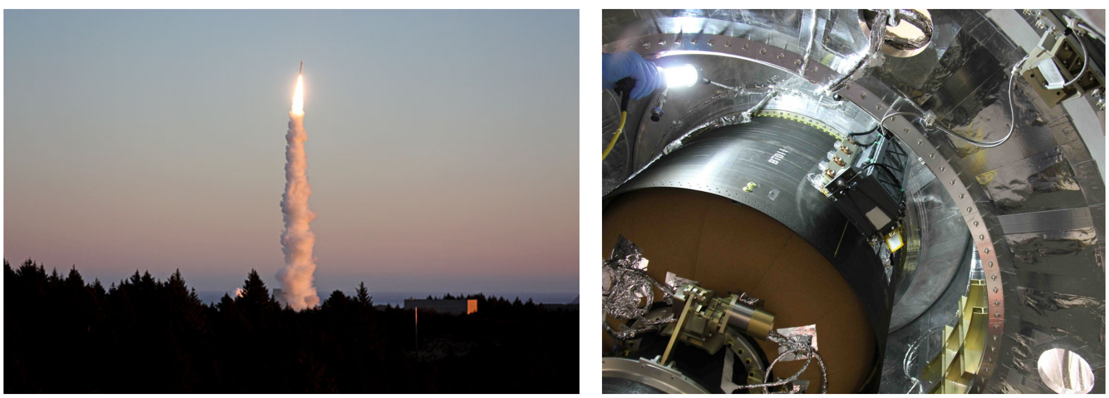
5.5 STP-S26

This mission launched on a Minotaur IV rocket on 19 November 2010, from the Kodiak Launch Complex in Alaska. This rocket did not contain a primary spacecraft, but instead launched four ESPA-class spacecraft and two CubeSats. These microsatellites included STPSat-2, FalconSAT-5, FASTSAT, and FASTRAC. This rocket contained one standard Mk. III P-POD holding RAX-1, and one NASA-modified P-POD containing O/OREOS.

FASTRAC, from the University of Texas (UT) at Austin, won the 3rd University Nanosatellite Competition in 2004. FASTRAC contained two similar satellites that separated after several weeks and performed thruster, relnav, attitude, and crosslink experiments. It also provided flight heritage for components that will go into UT's BEVO-X CubeSat [45, 46]. Using the amateur radio service, these satellites contained several different Hamtronics crystal-controlled transmitters and receivers for communications, connected to a Kantronics KPC-9612+ TNC [47].

FASTSAT contained several experiments, and also housed another NASA-modified P-POD with NanoSail-D2 loaded inside. FASTSAT was programmed to deploy NanoSail-D2 after one week. It appeared that the NASA-modified P-POD door did open at the preprogrammed time, but NanoSail-D2 was not ejected because no additional objects were detected by NORAD. It was presumed that NanoSail-D2 was stuck inside the NASA-modified P-POD. Several weeks later, during a FASTSAT orbit maneuver, NanoSail-D2 did successfully deploy, and started transmitting almost immediately.

This was the first CubeSat launch where the Keplerian elements were restricted by NORAD, due to the sensitive primary payloads. Elements were sent to the individual teams for redistribution.



(a) Launch from Kodiak [51]. (b) RAX-1 P-POD mounted.

Figure 19: STP-S26 launch.

5.5.1 RAX-1

The Radio Auroral Explorer (RAX-1) spacecraft was the first satellite funded through the National Science Foundation Space Weather program. The primary mission of this spacecraft was to characterize field-aligned irregularities of electron density in the auroral region. These irregularities disrupt communication and navigation signals in this region [48].

The ground-based bistatic radar transmited a high-power pulse, around 2 MW EIRP, using a large phased-array antenna. A radar receiver, built by SRI International, recorded both the direct radar pulse and the side scatter. The 1 MHz chunk of recorded spectrum was decimated from 1.2 GB to approximately 200 kB for downlink using an onboard Marvell PXA270 processor running at 500 MHz.

The communications subsystem consisted of an AstroDev Lithium-1 radio at 437.505 MHz, and a Microhard MHX-2400 2.4 GHz transceiver. The Lithium radio performed well, operating at 9600 baud GMSK and downloading 4.8 MB of commanded data to the ground. The Microhard radio was never turned on [49].

Since the radar receiver and the primary communications transceiver were in the same frequency band, a single quad turnstile antenna was switched between the two radios. The antennas were restrained for launch using fishing line and 1/8-watt burn resistors. In the center of the turnstile antenna was the 2.4 GHz patch for the Microhard radio.

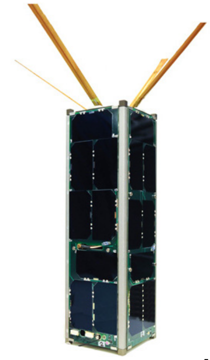


Figure 20: RAX-1 [49].

Solar cell corrosion, created by improperly stored solar cells, caused RAX-1 to slowly reduce functionality three months after launch, after one radar experiment was performed. RAX-1 was declared completely non-operational at the end of January 2011, and a failure analysis team determined that lack of protection diodes and coverglass on the solar cells were to blame for the premature failure [50].

5.5.2 O/OREOS

The Organism/Organic Exposure to Orbital Stresses (O/OREOS) 3U CubeSat continues with the common NASA Ames Bus, similar to GeneSat and PharmaSat. It carries two organic payloads and a new deorbit device. The first payload is similar to the earlier GeneSat and PharmaSat payloads, with organisms brought back to life in orbit, and growth rates measured to determine radiation effects. The second payload exposes the organisms to outer space using an external carousel, and measures cell growth using the sun as a UV source [52].

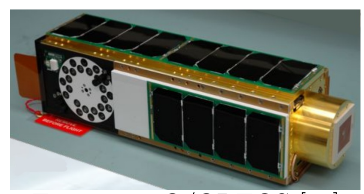


Figure 21: O/OREOS [54].

This satellite uses the same communication system as earlier NASA Ames CubeSats. It uses a Microhard MHX-2420 as the primary data transceiver, again with limited success. It also contains a Stensat UHF beacon at 437.305 MHz, transmitting 1200 baud AFSK with AX.25 formatting.

Due to the heavy spacecraft mass, a de-orbit device is included. Activated when the P-POD door opened, the de-orbit device uses a large spring to extend the end of the spacecraft by 28 cm to increase the satellite's surface area [53]. O/OREOS completed all of its science missions in May 2012, and has downloaded a total of 8 MB via the Microhard radio [54].

5.5.3 NanoSail-D2

While the first NanoSail-D spacecraft was lost in the Falcon 1 launch failure from the Kwajalein Atoll in August 2008, this second 3U flight model successfully achieved orbit after a delayed ejection from FASTSAT on 17 January 2011. The primary mission included successfully deploying the 10-square-meter sail on orbit, showing that the solar sail concept can de-orbit a small spacecraft [55].

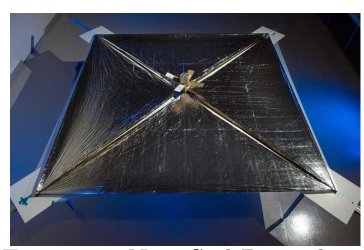


Figure 22: NanoSail-D2 with sail deployed [56].

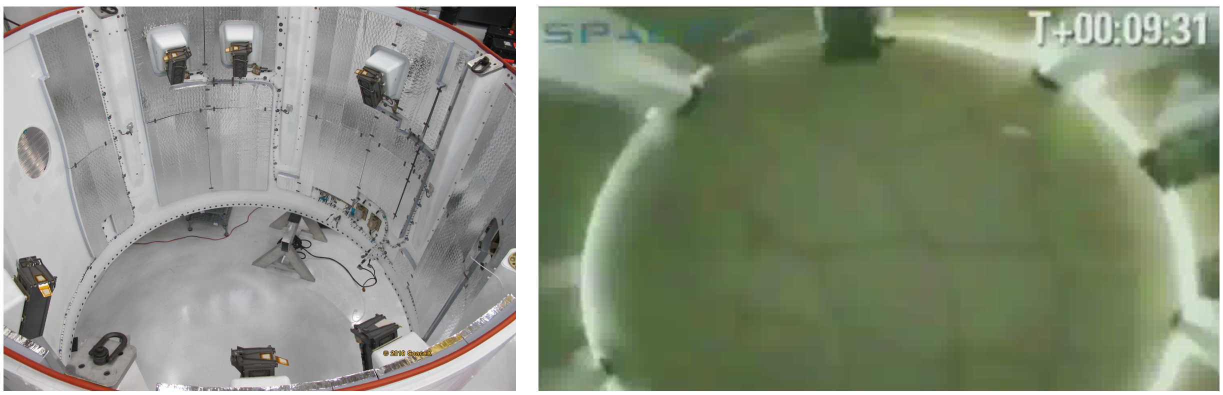
This spacecraft was built using the common 1U NASA Ames bus, very similar to GeneSat and PharmaSat, and a 2U solar sail unit, built by ManTech SRS and Marshall Space Flight Center. There were no solar panels on this satellite. NanoSail-D2 contained a Stensat beacon operating at 437.270 MHz and a Microhard MHX-2400 transceiver. The solar sail deployed as planned on 20

January 2011 at an altitude of 640-km, and the satellite deorbited 240 days later on 17 September 2011 [56, 57].

5.6 Falcon 9-002

This was the first CubeSat launch from Kennedy Space Center in Florida, and the first launch of CubeSats from a SpaceX rocket. This launch contained six Mk. III P-PODs, mounted to the trunk section, which deployed after the Dragon Capsule separated. This was the second Falcon 9 launch under the NASA Commercial Transportation to Space (COTS) program, and the purpose of this launch was a re-entry test of the Dragon Capsule. The eight satellites were deployed in a 300-km circular orbit, and all have deorbited.

SRI International and Cal Poly performed integration services for this launch. This rocket blasted off on 8 December 2010. All P-PODs deployed successfully, and the Dragon Capsule successfully returned to earth [58].



(a) P-PODs mounted to trunk.

(b) Dragon pulling away. Three P-PODs can be seen as dark objects at the top and right sides of the image.

Figure 23: Falcon 9 [58].

5.6.1 Perseus (4)

The mission of the four 1.5U CubeSats from Los Alamos National Lab was to demonstrate the ability to rapidly build a small satellite, gain CubeSat build and operations experience, and prove that COTS components can survive the space environment. These four satellites were built at in under six months [59].

The communications system was based around a single-chip transceiver into a dipole antenna. Successful tests of the communication system included two- and three-way communication and collection of telemetry.

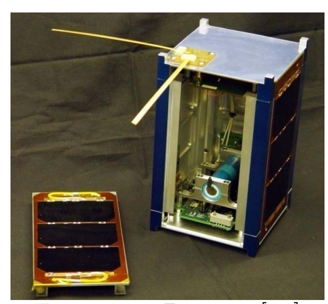


Figure 24: Perseus [60].

5.6.2 QbX (2)

These two identical 3U spacecraft were the first in the Colony series of spacecraft, bought by the National Reconnaissance Office (NRO) from Pumpkin Inc. The main purpose was to explore the suitability of small spacecraft for experimentation and technology development. The payload was a communications experiment [61].

The Colony 1 Pumpkin bus is a standard 3U CubeSat Kit with extra modifications, including an IMI-100 ADACS unit, deployable solar panels, and a pluggable processor module architecture. The power system was a Clyde Space EPS unit, modified to remove several phantom-discharge flaws found in the standard COTS unit. The flight processor was a SiLabs C8051F120.

Each spacecraft contained two radios. The tracking, telemetry, and command (TTC) radio was a custom design at 450 MHz with a data rate of 9600 baud GMSK and 1 watt of output power. Both the TTC and payload radio fed a single nadir-pointing, deployable quadrafilar helix antenna. The TTC radio performed well, but the payload radio had issues that were never solved, and success was limited. The ground segment consisted of the first version of the Mobile CubeSat Command and Control (MC3) system, developed by NRL [62].

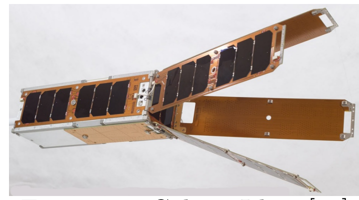


Figure 25: Colony I bus [62].

5.6.3 SMDC-ONE

The Space and Missile Defense Command Operational Nanosatellite Effect (SMDC-ONE) 3U satellite was built by Miltec for SMDC as a rapid-development spacecraft. This was the first Army-built spacecraft in over 50 years, and signaled the Army's return to space [63].

It was powered by the standard COTS power system from Clyde Space. The communications subsystem was built by Pericle Communications of Colorado Springs, and contained a quad turnstile antenna on each end of the spacecraft, one for receive and one for transmit [64].

The spacecraft was designed to relay short messages from unattended ground sensors, and send short messages between established ground stations in Huntsville, Ala., and Colorado Springs, Colorado. It successfully completed the mission before deorbiting after about 35 days. Students from nearby universities performed operations on this satellite [66].

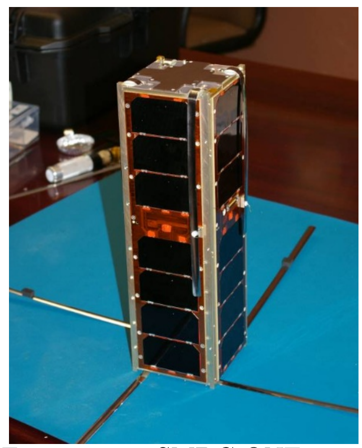


Figure 26: SMDC-ONE engineering model [65].

5.6.4 Mayflower

The Mayflower/Caerus 3U CubeSat was a collaboration between Northrop Grumman, who built the propulsion and power payload, and the Space Research Engineering Center at the University of Southern California, who integrated the payload into a Pumpkin 1U kit. The satellite also contained a high-power fold-out solar array, rated at 48 watts [67].

Mayflower's primary communication system consisted of a Microhard MHX-425 at 437.000 MHz. Mayflower also contained a 1 watt Stensat Radio Beacon, with a data rate of 1200 baud AFSK at 437.600 MHz [68]. Both radios shared a turnstile antenna, positioned between the 1U bus and 2U payload. The team applied for an experimental license for the Microhard and an amateur license with IARU coordination for the Stensat beacon, but neither licensing process was completed before launch.

Figure 27: Mayflower [68].

Strong UHF downlink beacons were heard from the satellite for one day only. It is theorized that the attitude control system was not strong enough to point the solar cells at the sun, causing the satellite to lose power. No uplink commands were ever received by the spacecraft. The propulsion payload was never exercised. Due to the low orbit and fold-out solar panels, Mayflower deorbited on 22 December 2010, only 14 days after launch [69].

5.7 ELaNa-1/Taurus XL

This launch was the first in the Educational Launch of Nanosatellites (ELaNa) missions, managed by the Launch Services Program at Kennedy Space Center. This program was started by Garret Skrobot in 2010 as a way to get student's spacecraft into orbit.

This Taurus XL launch from Vandenberg Air Force Base in California contained the Glory satellite as the primary, a 545-kg satellite whose mission included measuring total solar irradiance and taking pictures of clouds. It was the first launch of a Taurus XL since the Orbiting Carbon Observatory satellite failed to achieve orbit in February 2009 after the fairing failed to separate [70].

Inside a single Mk. III P-POD mounted next to the upper-stage motor were three 1U satellites from a consortium of universities in Kentucky, the University of Colorado at Boulder, and Montana State University:

- **KySat-1** was the first satellite from Kentucky Space, a consortium of universities and companies in Kentucky. Its primary mission was K-12 outreach, and it used a Stensat digital transponder so that students could send messages through the spacecraft. It also contained a Microhard MHX-2400 transceiver [71].
- **Hermes** was the first CubeSat built by the Colorado Space Grant Consortium at the University of Colorado, Boulder. This 1U's primary mission included flight testing of a high-speed S-band radio based on the Microhard MHX-2400, and development of a spacecraft bus. The communications subsystem was built around a Yeasu VX-7R transceiver operating under the amateur radio service at 437.425 MHz with 1 W output power into a dipole antenna [72].
- **Explorer-1'** from Montana State University measured the radiation belts around the earth, using a Geiger tube. The satellite contained a CC1000 radio transceiver at 437.305 MHz with 850 mW of output power into a dipole antenna. The second flight unit was flown in October 2011 [73].

This launch failed to achieve orbit on 4 March 2011 after the fairing failed to separate, the same problem the previous Taurus XL launch had. All of the satellites are now in the South Pacific ocean. While this first launch of the ELaNa program was not a success, the other ELaNa launches will use different rockets, increasing the chance of success for the overall program.

Figure 28: P-POD being mounted to the aft end of the Taurus XL [74].

5.8 PSLV-C18

This rocket blasted off on 12 October 2011 from the Satish Dhawan Space Center in Sriharikota, India. The primary satellite is the Megha-Tropiques satellite, which measures the water cycle in the tropics. The other secondary satellites were SRMSat and VesselSat-1, a satellite AIS receiver. All four satellites on this launch were delivered into a 860-km circular orbit at 20°. The single 1U CubeSat was deployed by a custom system built by the Indian Institute of Technology (IIT) Kanpur, with help from ISRO [75].

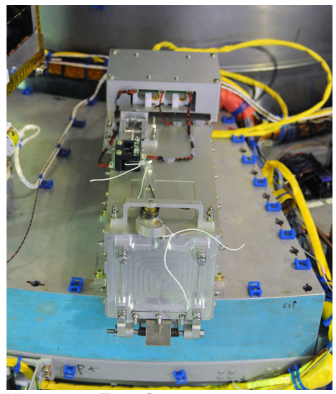


Figure 29: IIT Kanpur Deployer system on the upper stage.

5.8.1 Jugnu

This 3U CubeSat was designed and built entirely in India by students at IIT Kanpur, under the guidance of ISRO engineers. Its primary goal was education and development of procedures and infrastructure related to small satellite development. The primary payload included an IR camera, GPS receiver, custom-built reaction wheels, and an Analog Devices COTS inertial measurement unit [76, 77].

Figure 30: Jugnu [76].

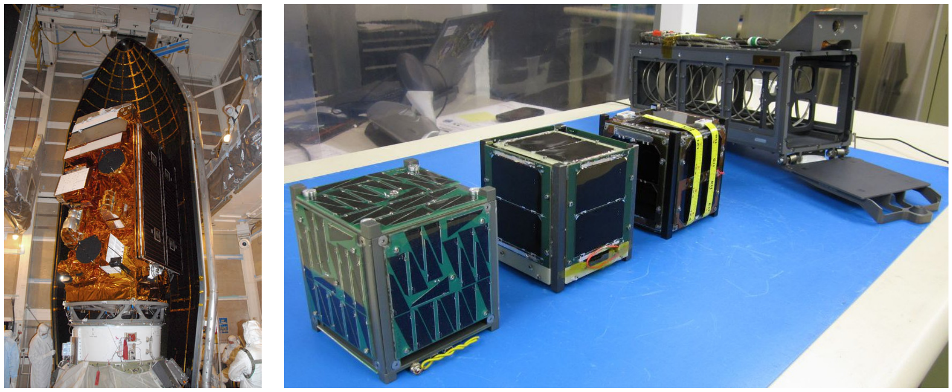
The satellite was built around a 3U Pumpkin structure, with a Pumpkin MSP430 and AT91SAM7 ARM 7 processor, and custom built power system. The communication subsystem contained three radios. The command receiver was a custom design based on an Analog Devices ADF7020-1. The CW beacon transmitter at 437.275 MHz was also a custom design, based on a MAX1472 crystal-based transmitter, and outputted 10 mW of power. The 2400 baud FSK transmitter at 437.505 MHz was a custom design based on the Chipcon CC1070 with a RF5110G power amplifier for 1 watt output power [78]. All radios were amateur-licensed and used separate monopole antennas that deployed from the center of the spacecraft.

5.9 ELaNa-3/NPP

This Delta II blasted off from Vandenberg Air Force Base on 28 October 2011 into a 800- by 400-km orbit at 97° [79]. The primary payload was the NPOESS Prepatory Project (NPP), a precursor to the next generation of military weather satellites, and three Mk. III P-PODs from Cal Poly housed six satellites. This was the first successful launch of the ELaNa Program.

After P-POD deployment, NORAD was able to track only five objects, and it appears that M-cubed and HRBE are in close proximity or attached to each other. While the reason is unknown, the

M-cubed team believes that the satellites are stuck together due to the permanent magnets [80, 81]. The HRBE team is not convinced [87].



(a) NPP, with the P-PODs mounted in the lower right.

(b) AubieSat-1, HRBE, and M-Cubed before integration.

Figure 31: ELaNa-3/NPP launch [79].

5.9.1 AubieSat-1

AubieSat-1 was the first CubeSat from Auburn University. Its primary mission was education, and contained a science experiment testing new protective plastic films installed over the solar cells.

AubieSat-1's 1U structure was built by students, and contained an Atmel ATmega1281 as the main microprocessor. The custom-built power subsystem used an Atmel XMega128A1 for maximum peak-power tracking and charge control of the lithium-ion batteries.

The transmitter was based on a Melexis TH72011 as the exciter, with a NEC discrete power amplifier that transmited about 800 mW on 437.475 MHz under the amateur satellite service. The modulation scheme was 20 WPM CW. The spacecraft receiver used a Melexis TH71102 single-chip IC with a NEC UPC3227TK low-noise amplifier [82].

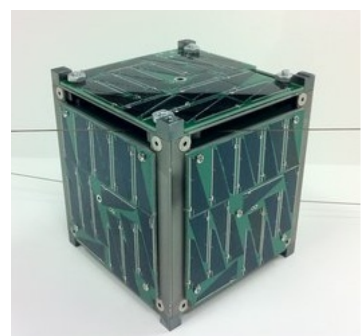


Figure 32: AubieSat-1 [83].

AubieSat-1's downlink CW was strong enough to decode, but uplink commands were not received by the spacecraft after launch. The team theorized that the separate Nitinol 'memory wire' uplink and downlink dipole antennas did not deploy. The team traveled to Montana State University to test this theory on MSU's 1.5 kW amplifier, originally purchased for HRBE, and a link was established to the spacecraft [83].

5.9.2 DICE (2) *

The Dynamic Ionosphere CubeSat Experiment (DICE) consists of two 1.5U CubeSats from the Space Dynamics Laboratory at Utah State University. These identical satellites contain a langmuir probe for electron density measurements, several electric field probes, and a magnetometer. This is the second mission launched for the NSF CubeSat Program [84].

Each DICE satellite contains a Cadet radio from L3 Communications. It operates at 465 MHz in the Meteorological-satellite band. Due to severe power flux density restrictions placed on this band, the transmitter power is about 1 watt, spread out over the 3 MHz BPSK signal. This power restriction requires a big dish to receive the signals; 18-m dishes at both NASA Wallops and SRI International were used. Local narrow-band interference prevented the dish at SRI International from decoding much data. After the forward error correction, the bit rate is 2.6 Mbps. The total data downloaded as of April 2013 is 8.4 GB of data for both satellites [85].

Both DICE and CINEMA (launched on ELaNa-6, see Section 5.11.7) were licensed by the NSF Spectrum Committee through the NTIA, which authorizes US-Government-funded and -operated satellites. After this process was complete, the NTIA stated that these types of NSF-funded but contractor-operated missions should be licensed through the FCC, either experimentally or through the appropriate service. NSF teams should get experimentally licensed in the future [5].

Figure 33: Two DICE spacecraft with stands [84].

5.9.3 HRBE

Originally named Explorer 1 Prime Flight Unit 2, the Hiscock Radiation Belt Explorer (HRBE) is the first CubeSat from the Space Science and Engineering Laboratory at Montana State University to achieve orbit. Their earlier MEROPE and Explorer 1 Prime satellites failed to reach orbit on the earlier Dnepr-1 and ELaNa-1/Taurus XL rocket failures. The primary mission is student education and process development, with a secondary science mission measuring the Earth's radiation belt using a Geiger tube [86].

HRBE's communication system is based on a ChipCon CC100 radio at 437.505 MHz, outputting 850 mW into a monopole antenna. The packet format is standard AX.25 1200 baud FSK. As demonstrated by CP2 and CP6, the CC1000 receiver is quite deaf, and for the first few months, no uplink commands were received. After traveling to SRI International's 60-ft dish, the team proved that a link deficiency was the only problem, and purchased a 1 kW amplifier for their ground station. Regular contacts with the spacecraft were initiated [87].

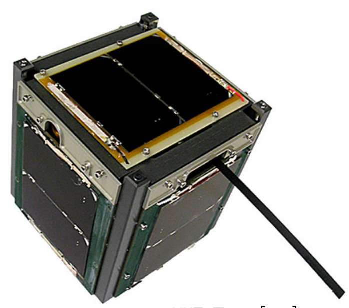


Figure 34: HRBE [87].

Unfortunately, HRBE completely reboots itself from read-only memory every 24 hours. Therefore, any change in configuration to the satellite, including beacon rate, science detector thresholds, and high-voltage settings, are reset to the defaults every day. This makes getting real science from the spacecraft challenging. In September 2012, the satellite began losing power, could no longer keep itself alive through eclipses, and sometimes browned out after transmitting a packet [88]. This indicated that its batteries were failing, but by November the problem had rectified itself and the satellite was back to normal operations [89].

5.9.4 M-Cubed

A collaboration between the NASA Jet Propulsion Laboratory and the University of Michigan, the Michigan Multipurpose Minisat's 1U payload was to flight test and qualify a Virtex-5QV FPGA for JPL. A small 1600x1200-pixel OmniVision 2655 CMOS imager generated data for the FPGA [90].

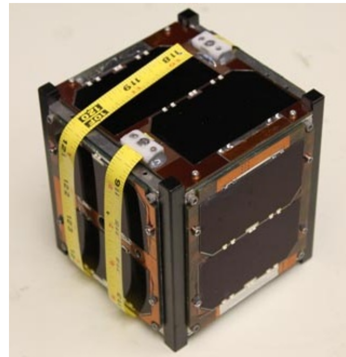


Figure 35: M-Cubed [91].

The main processor on M-Cubed was a Stamp9G20. The power and structure subsystems were designed by students at the University of Michigan.

The spacecraft used two AstoDev Lithium-1 radios, one for uplink and the other for downlink. The amateur-licensed downlink of 1 watt transmitted 9600 baud FSK at 437.485 MHz. The antennas consisted of two monopoles. Beacons were very weak to decode, so very few packets were decoded and sent in by hams around the world [91]. The team traveled to SRI International's 60-ft dish to try to uplink commands and decode more telemetry from the spacecraft, but the effort was not successful.

5.9.5 RAX-2

This satellite is the flight backup of the earlier RAX-1 CubeSat that launched on STP-S26 in November 2010. RAX-2 was built to correct the RAX-1 solar panel failure and continue the RAX mission. It's subsystems are composed of a combination of RAX-1 backup hardware and new components. RAX-2's science mission is a complete success, and it has seen numerous field-aligned irregularities over the course of its 32 experiments [92, 93].

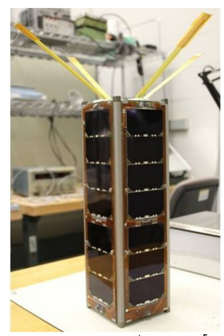


Figure 36: RAX-2 [49].

The communications system is an AstroDev Lithium-1 radio at 437.345 MHz 9600 baud GMSK, the same as RAX-1 [94]. It has downlinked 242 MB of science and telemetry data. The Microhard 2.4 GHz transceiver was exercised in orbit, but the team realized that the very low effective data rate of this radio–around 10 kbps–and high current draw means that this radio is a more effective heater than transceiver.

5.10 Vega VV01

Originally scheduled for 2008, the maiden flight of the Italian-built VEGA rocket lifted off on 13 February 2012 from Kourou, French Guiana. Since this was the first launch of this rocket, there was no primary payload. The main secondary satellites were LARES, a laser relativity satellite, and ALMASat-1, a technology demonstration microsatellite from the University of Bologna.

This rocket contained three Cal Poly-built Mk. III P-PODs for the seven 1U spacecraft. Due to CubeSat design and fabrication issues and delays with the rocket, the other two slots were abandoned, and mass models were wired onto the P-POD pusher plate. SwissCube found an earlier launch, and HiNCube will be on a commercial launch in the near future. The rocket placed the CubeSats into a 308- x 1427-km orbit at 69.5°.

Figure 37: Xatcobeo, e-st@r, and Goliat CubeSats with their integration teams.

5.10.1 Xatcobeo

This 1U CubeSat was built by students at the University of Vigo, in collaboration with the Spain National Institute for Aerospace Technology (INTA). The primary purpose is student education, with three payloads including an FPGA-based software-defined radio, a non-ionizing radiation dosimeter, and a new solar panel deployment mechanism [95].

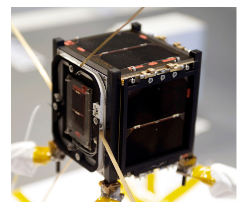


Figure 38: Xatcobeo [95].

The power system for Xatcobeo is from Clyde Space, with two deployable solar panels in addition to the body-mounted panels. The main processor is a Vertex-II FPGA [96]. The communications system is a U482C from GomSpace, transmitting 1200 baud MSK at 437.365 MHz in the amateur radio service. It also contains a CW beacon at 20 WPM with housekeeping data. The radio transmits into a custom-designed turnstile antenna [97].

5.10.2 ROBUSTA

The Radiation On Bipolar for University Satellite Test Application (ROBUSTA) CubeSat was built by students at the University of Montpellier 2 in France. The main mission of this 1U CubeSat was student education, and the primary payload was a radiation test of two integrated circuits, including the radiation-sensitive LM139 voltage comparator and LM124 voltage amplifier.

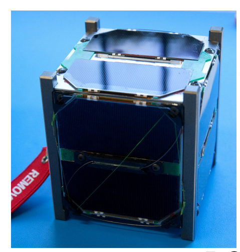


Figure 39: ROBUSTA [100].

The structure was custom-built by students at the university, and the main processor was a PIC18F4580 running at 4 MHz. The power system was custom-built and includes triple-junction solar cells from Azurspace and a single lithium-ion battery.

ROBUSTA's transmitter was based on a MC12181 synthesizer and MAX2608 VCO. It transmitted 800 mW at 437.325 MHz in the amateur satellite service. The data rate was 1200 baud AFSK with a AX.25 format. The beacon period was three minutes, and the antenna was a dipole [98].

A power system defect prevented the batteries from charging. Faint signals were heard after launch, but no telemetry was decoded. Reset commands were received by the spacecraft, but the satellite died when the batteries lost their charge [99, 100].

5.10.3 e-st@r

Built by the Politecnico di Torino in Turin, Italy, this 1U CubeSat's main mission was student education, and the development and testing of an attitude determination and control system [101].

This university's previous small satellite PiCPoT was a 13-cm cube that flew on the failed Dnepr-1 mission in July 2006 [102].

The main processor and structure was CTOS unit from Pumpkin, and the power system was from Clyde Space [103].

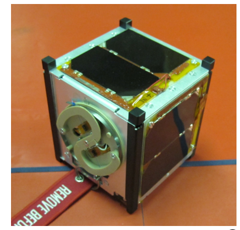


Figure 40: e-st@r [105].

e-st@r used a commercial Radiometrix BHX2-437-5 transceiver outputting 500 mW, connected to a PIC16F that acted as the TNC. The satellite transmitted in the amateur satellite service at 437.445 MHz with a 1200 baud AFSK modulation scheme and AX.25 formatting. Packets were received by ground stations across Europe, but no data was decoded. It appeared that there was a power problem , as the signal kept getting weaker before the satellite failed a few weeks after launch [104, 105].

5.10.4 Goliat

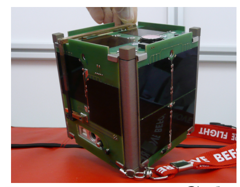


Figure 41: Goliat [107].

This 1U CubeSat was primarily built by the University of Bucharest under the supervision of the Romanian Space Agency. Smaller groups at other universities also helped. As was the case for all CubeSats on this first VEGA launch, Goliat's primary objective was student education. Its science payloads included a radiation detector, a micro-meteoroid detector, and a narrow-angle 3 megapixel optical imager with a 57-mm focal length [106].

The on-board computer consisted of several MSP430 with a 2 GB SD card, and the power system was designed by students. The structure was a COTS unit built by Pumpkin. This spacecraft transmitted 500 mW with an Alinco DJ-C7 transceiver and FX614 TNC under the amateur satellite service on 437.485 MHz, with 1200 baud AFSK modulation scheme and AX.25 formatting. This radio also transmitted a CW beacon at 20 WPM [107]. The UHF antenna was deployed with a small motor. This satellite also contained a Microhard MHX-2420 transceiver with a quarter-wave monopole antenna, although a link was not established with this radio during the satellite's limited 1 week lifetime [108, 109].

5.10.5 PW-Sat

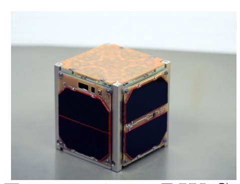


Figure 42: PW-Sat [111].

Built by students at the Warsaw University of Technology (WUT) and in collaboration with Space Research Center of the Polish Academy of Sciences, this 1U CubeSat's mission was orbital debris mitigation. The primary payload contained a 1.2-meter deployable tail, with solar cells along the side, intended to reduce the orbit lifetime by one-third of a year [110].

The structure of this spacecraft was built by students at WUT. The main processor consisted of an ARM7 NanoMind A702 module from GomSpace.

The single ISIS TRXUV transceiver had two modes, and transmitted 200 mW on 145.900 MHz with an amateur license. The CW mode transmitted basic telemetry information and messages from the team at 12 WPM. The high-speed downlink mode transmitted a 1200 baud BPSK signal with AX.25 formatting [111]. Due to uplink communication and power difficulties, the tail was not deployed. PW-Sat ceased functioning on 23 Dec 2012.

5.10.6 Masat-1

Masat-1 is the first CubeSat from the Budapest University of Technology and Economics in Hungary. Its main mission is student education, and to create processes and procedures for their next CubeSat. The main payload is a visible camera, with a 640x480 pixel image area and a ground resolution of 2- to 10-km, depending on actual altitude. The team has taken many pictures of the Earth, including several mosaic and anaglyph 3D [112].

The main processor of Masat-1 is a dsPIC33F, which also acts as the TNC. The custom power system uses PIC12 microcontrollers for peak power tracking.

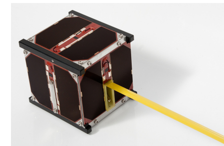


Figure 43: Masat-1 [114].

The satellite uses a Si4432 single-chip transceiver at 437.345 MHz, with an external power amplifier and LNA. Within a one-minute period, it transmits a 100 or 400 mW CW signal with the callsign and limited telemetry, then switches to a 625, 1250, or 5000 bps GFSK signal for higher-speed transmission [113]. The GFSK signal is FEC-encoded with a binary Golay code, and the team provides client software for beacon decoding and submission, as well as a smartphone application for picture viewing [114]. A USB dongle receiver was also developed [115].

5.10.7 UniCubeSat-GG

The 1U UniCubeSat-GG satellite was the first CubeSat built by the Sapienza University of Rome. Its primary purpose was student education, and the payload consisted of a two-element gravity gradient boom stabilization system. Solar panels were installed on the boom, and the distance between the tip masses was approximately 90 cm. Students built a custom structure, and the power system was a Clyde Space EPS board with Spectrolab TASC cells. The main processor was an MSP430 [116].

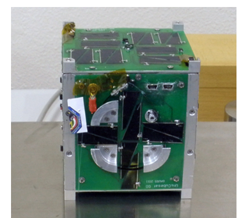


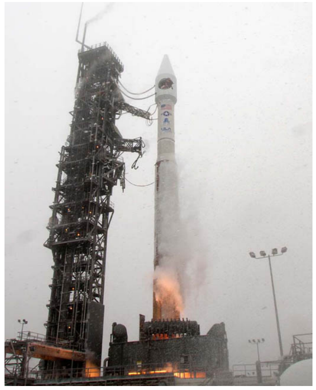
Figure 44: UniCubeSat-GG [116].

This spacecraft had a custom AstroDev transceiver and transmitted on 437.305 MHz under an amateur radio license. The data rate was 9600 baud GFSK with AX.25 formatting and 500 mW output [117, 118]. It also contained a CW beacon. Faint signals were heard from this CubeSat in the two days after launch, but it is theorized that the power system failed after several days and the spacecraft went silent [119].

5.11 ELaNa-6/NROL-36

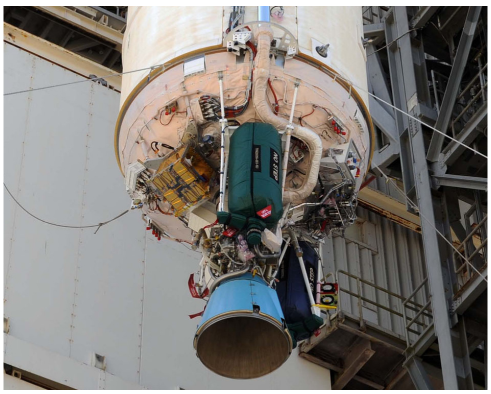
This was the first launch of CubeSats from an Atlas V from Vandenberg Air Force Base, California. The primary spacecraft was classified, so the same ephemeris restrictions were present as on the previous STP-S26 launch from Kodiak, Alaska (see Section 5.5). The NRO and NASA worked together for this launch, with NRO manifesting five of the eight P-PODs, and NASA's ELaNa program filling the other three.

This was the first flight of the Naval Postgraduate School CubeSat Launcher (NPSCuL). Just a five-sided box, the NPSCuL housed eight regular Mk. III P-PODs. Cal Poly and SRI International provided integration services. The integrated NPSCuL with CubeSats was called OUTSat; it was mounted on the Aft Bulkhead Carrier (ABC) of the Atlas V launch vehicle [120]. This rocket was launched on 13 September 2012, and the CubeSats were deployed into a 770- x 480-km orbit with an inclination of 64°.



(a) Vandenberg Launch.

(b) NPS and Cal Poly students with OUTSat.



(c) NPSCul mounted to Atlas V.

(d) AeroCube-4 picture of the Centaur upper stage after deployment.

Figure 45: ELaNa-6/NROL-36 launch [121].

5.11.1 SMDC-ONE (2)

The two 3U SMDC-ONE satellites on this launch were flight backups from the previous Falcon 9-002 launch in December 2010 (see Section 5.6.3). The communications subsystem was built by Pericle Communications of Colorado Springs, and contains a quad-turnstile antenna on each end of the spacecraft, one for receive and one for transmit [64].

5.11.2 AeroCube-4 (3)

The three 1U AeroCube-4 satellites on this launch are an evolutionary step from the previous AeroCube-3 satellite. New features include fold-out solar panels, more advanced cameras, a new rate gyro, and a non-inflatable deorbit device [122].

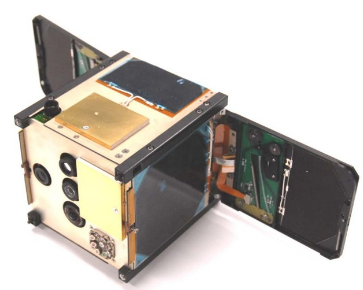


Figure 46: Single AeroCube-4 [122].

All three CubeSats contain two FreeWave MM2 radios for redundancy, the next generation of the radios used on the previous AeroCube satellites. However, the AeroCube-4 satellites also contain a new, advanced, high-bandwidth radio based on the Chipcon CC1101 single-chip transceiver. The data rate is variable between 1.2 and 500 kbps with an output power of 1.3 watts. This radio is experimentally licensed at 915 MHz and uses encryption [123, 124].

5.11.3 Aeneas

Aeneas is a 3U CubeSat built by the Space Research Engineering Center at the University of Southern California. The main mission is tracking cargo shipping containers as they cross the ocean. The satellite listens for existing S-band transmitters on containers that communicate within shipping ports. The satellite is based on their earlier Mayflower satellite with a Pumpkin Colony I bus [125].

The primary mission requires a 0.5-m deployable S-band dish, which occupies 1.5U of this spacecraft. Once a link to the shipping containers on the open ocean is closed and identification data transferred, accurate attitude knowledge is used to geolocate the container on the surface of the earth [126].

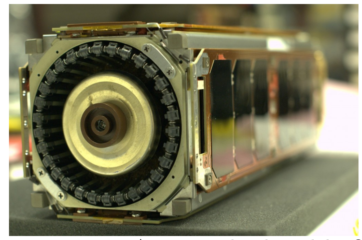


Figure 47: Aeneas deployable S-band dish [126].

This satellite uses an experimentally licensed Microhard MHX-425 transceiver at 437.0 MHz for its primary communications, exactly the same radio used on their previous Mayflower CubeSat [127]. As documented with HawkSat-1, their previous mission Mayflower, the NASA Ames CubeSats, and RAX satellites, the Microhard is not designed for space and performs poorly. The team traveled to SRI International's 60-ft dish to see if a bigger dish would help close the link, but the results were inconclusive.

The satellite also contains a 1 watt Stensat radio beacon at 437.600 MHz, with a data rate of 1200 baud AFSK, licensed under the amateur satellite service. The antennas for both the Microhard transceiver and Stensat transmitter are monopoles on the end of the 3U fold-out side panels [69].

5.11.4 CSSWE

The 3U Colorado Student Space Weather Experiment (CSSWE) CubeSat was the sixth NSF-funded CubeSat project, and third to be launched. The primary science mission is to measure the energetics of solar-produced relativistic electrons and protons during solar flares, and to study how they impact the Earth's outer radiation belts. The secondary mission is student education [128, 129].

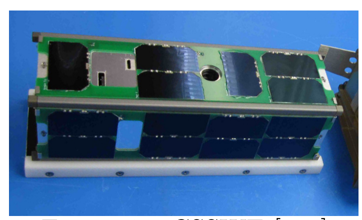


Figure 48: CSSWE [129].

This spacecraft uses the standard Pumpkin CubeSat Kit MSP430F2618 main processor, solid Pumpkin structure, and a custom-built power system without peak power tracking. A passive magnetic system is used for attitude control [130].

CSSWE uses an AstroDev Lithium-1 radio on the spacecraft, transmitting on 437.345 MHz at 9600 baud GMSK with an experimental license. The monopole antenna protrudes one end of the spacecraft. The ground station at the University of Colorado uses a Kenwood TS-2000, and communications have worked well [131].

5.11.5 CP5

This 1U satellite built by Cal Poly was their fourth satellite to successfully reach orbit. Its primary purpose was student education, and the main payload was a solar sail deployment experiment. Students were to measure the drag of the 0.5-square-meter sail via orbit decay and optically measure the degradation of the sail in orbit.

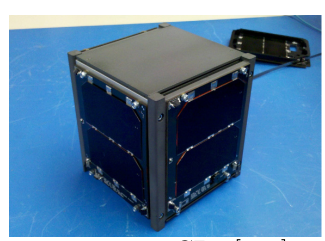


Figure 49: CP5 [132].

As was the case for the previous CP-series of satellites, the main processor was a PIC18LF6720, the structure was designed and built by students, and the power system was custom built without peak power tracking. The communications system was based on one CC1000 single-chip transceiver, with the same PIC processors for the TNC. CP5 transmitted 500 mW at 437.405 MHz into a dipole antenna. This transceiver performed poorly, with typically one uplink command received by the satellite per pass. Downlink was more reliable, with several beacons decoding per pass.

Cal Poly attempted to deploy the sail, but lost contact with CP5 shortly thereafter. No change in altitude was noticed in the data. The last beacon was heard in January 2013 [132].

5.11.6 CXBN

Primarily built by students at Morehead State University (MSU) in Kentucky, this 2U CubeSat's primary mission is student education and the starting of a space program at MSU. The primary payload is a cadmium zinc telluride detector array that measures the cosmic X-ray background radiation in the 30-50 kEv range. Other smaller payloads include a COTS MEMS gyro and a novel star sensor [133].

Figure 50: CXBN [133].

The main processor is a 25 MHz MSP430, and the power system is a custom in-house design with four lithium-ion 18650 cells for energy storage. The structure was custom built at MSU, and holds four deployable solar panels. The entire spacecraft is spin-stabilized.

The communications subsystem is built around an AstroDev Lithium-1 radio, transmitting 9600 baud GFSK at 437.525 MHz with 1.5 watts of power in the amateur satellite service. The antenna is a turnstile [134]. Communications with CXBN were spotty from the beginning. For an unknown reason, the beacon was very weak, and few stations copied telemetry. Command uplink was also difficult. MSU owns and operates a 21-meter dish nearby, but UHF feeds are not installed [135].

5.11.7 CINEMA

CINEMA is UC Berkeley's first CubeSat, and its STEIN instrument will measure energetic ions, electrons, and neutrals at high ecliptic latitudes. This project is funded by the NSF's CubeSat program, under the direction of Therese Jorgensen [136]. Kyung Hee University in South Korea is building two more replica satellites for higher-precision measurements. These CubeSats will be launched on a Dnepr rocket in the middle of 2013 [137].

The main processor of CINEMA is a Pumpkin CubeSat Kit with pluggable dsPIC33FJ256 module [138]. The structure was built by students, and the power system is a Clyde Space EPS module. The instrument interface board contains an Actel Igloo FPGA, and controls the S-band radio, STEIN science instrument, and magnetometer developed by Imperial College in London.

Figure 51: CINEMA [139].

The downlink transmitter of CINEMA is an Emhiser EDTC-01DEA running at 1 MBit/sec FSK. It's licensed through the NTIA in the 2200-2290 MHz Space Research band. It is the second CubeSat licensed for this band, after CanX-2 in 2008. However, the Igloo FPGA can't transfer data from the SD card to the radio very quickly, so half of the downlink data is stuffing frames, reducing the effective throughput to 0.5 MBit/sec [139].

UC Berkeley uses an existing 11-m dish for their ground station receiver. This dish also communicates with their other small satellites, so downlinks must be scheduled. This 2.2 GHz downlink system performed well [140]. However, there are some issues with the uplink receiver or antenna system on the spacecraft, and limited commands have been received by the satellite. The team traveled to SRI International's 60-ft dish to help close the link, but results were mixed due to other issues on the spacecraft.

5.11.8 Re

Re is a 3U telescope looking for near-Earth space debris. The payload was built by Lawrence Livermore National Laboratory and integrated by the Naval Postgraduate School (NPS) into a 3U Colony II bus, built by Boeing and funded under the Colony program at the NRO. This satellite is one-half of the Space-Based Telescopes for Actionable Refinement of Ephemeris (STARE) project. The other CubeSat was manifested on this launch, but wheel problems with the bus prevented its integration into the NPSCul [141, 142].

This is the first launch of the Colony II bus. The communications system of this bus is based around a modified AstroDev Helium He-100 radio. Downlink is at 915 MHz FSK, with a data rate of 57.6 kbps and AX.25 packet formatting.

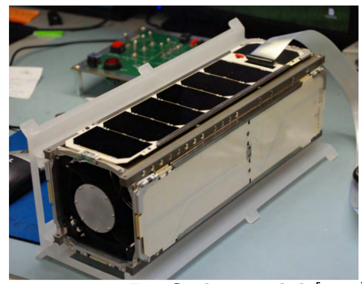


Figure 52: Re flight model [143].

The spacecraft downlink is provided through the Mobile CubeSat Command and Control (MC3) system, a ground station network being jointly developed by the Naval Research Lab and NPS. It is based on COTS hardware, and includes Icom IC-9100 radios, Yaesu G-5500 rotators, and a GDP Space Systems 4425D software-defined receiver. The "mobile" specification implies that the 1/2 rack of radios and computers can be shipped anywhere in the world and installed within as little time as a single day [144].

Re launched with mis-configured software, so its solar panels and antenna did not deploy automatically. It is unclear whether the single uncovered solar panel can provide enough power to keep the bus alive or burn the nichrome wires on the deployables. NPS traveled to SRI International's 60-ft dish to send commands to deploy the antenna and solar panels, but it's unclear whether the effort succeeded [145].

6 Conclusion

Tables 1 and 2 show that many of the university-class CubeSats are still using slower data rates. This is likely due to the ease at which hardware can be acquired. However, for some of the missions that require higher data rates, teams have taken the leap and purchased radios specifically designed for high-speed satellite communications. Success has been mixed, although that may be because the CubeSats with higher data rates are the first to have been built by their teams, and not all problems can be traced to communications.

Most first CubeSats, whether built by a university or by an organization with prior satellite experience, have limited success. Recent examples include Re, CINEMA, CXBN. RAX is a typical example, the first one failed after a few months but the second is performing well after 18 months in orbit. Teams should view their first CubeSat as a demonstration mission to work out all the bugs, and progress to science payloads with subsequent satellites.

Many people are interested only in the spacecraft's payload, as that is what funding is provided for. However, no matter how much money or time is spent on the payload, if the structure is poorly designed, the vibe test will not succeed; and if the communications or power systems don't work, then the satellite's payload won't work in space.

Uplink still also seems to be problematic. Of the 49 CubeSats discussed in this paper, only two were dead on arrival and never heard from in space. Of the remaining 47 CubeSats, seven never received any ground commands and did not perform their primary mission. With comparatively unlimited transmit power and antenna gain available for the uplink, the satellite should clearly hear the ground station. Teams should extensively test their command receiver before launch.

* The following applies to DICE (Section 5.9.2) only: This material is based upon work supported by Utah State University Research Foundation under Award No. CP0024199. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of Utah State University Research Foundation.

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