

Optimizing the Small Satellite Platform for Compelling Technology Demonstrations: Bandit/Akoya Proximity Operations and Rapid Integration

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Small satellites have the potential to advance space technology at a fraction of the cost and time of traditional large-scale spacecraft. Unfortunately, due to the volume constraint of miniaturized satellites, microscale spacecraft often lack the payload and bus space to support complex missions. Bandit/Akoya utilizes distributed design with a plug-and-play platform to perform proximity operations and rapid integration of two microscale vehicles and a host - all under 35 kg. Students are directly responsible for all program elements.

MAXIMIZING THE POTENTIAL OF SMALL SATELLITES

Small satellites have the potential to demonstrate compelling space technology at a fraction of the cost and time of traditional large-scale spacecraft. Unfortunately, due to the inherent volume constraint of miniaturized satellites, spacecraft that make it down to the under-5 kg scale often lack the payload and bus space to support complex missions.¹ Bandit/Akoya combines two such microscale vehicles with a nanosatellite host. The spacecraft utilize distributed design with a plug-and-play platform to perform cutting-edge proximity operations and rapid integration - all under 35 kg and \$70,000.

The Bandit/Akoya mission, summarized in Figure 1, is close-proximity maneuvering of a 3 kg redeployable free-flyer (Bandit) relative to a 29 kg host spacecraft (Akoya). To reduce the size of subsystems on Bandit, several are distributed to Akoya, such as docking and charging. At 12 x 12 x 18 cm, Bandit is smaller in volume than a triple CubeSat, yet it is capable of advanced demonstrations, including self-propelled orbits of Akoya, visual navigation, and autonomous control.

Akoya is a customizable bus. Its subsystem modules interconnect via a standard power/data protocol. They are immediately responsive to plug-and-play integration and testing. Akoya hosts two Bandits and can support additional payloads that conform to the protocol. By consolidating long-term functions onto one host, Akoya enables high-level missions of numerous microscale payloads simultaneously.

BANDIT/AKOYA OVERVIEW

Bandit and Akoya are student-built spacecraft started in 2003 by students and faculty of Aerospace Systems Lab (ASL) at Washington University in St. Louis (WU). Our goal is to optimize the small satellite platform for cutting-edge technology demonstrations. Students are directly responsible for all aspects of the project: design, fabrication, integration, testing, and management.

Bandit's mission is to flight-test proximity operations technologies, including docking, safe navigation within 5 m of a target vehicle, on-orbit charging, and image-based navigation. Operations are similar to those of MIT's SPHERES currently in use on the International Space Station;² Bandit extends those contained missions to the hands-off space environment. Orbital Express, a DARPA mission launched in March, 2007, will also perform on-orbit

THE MISSION

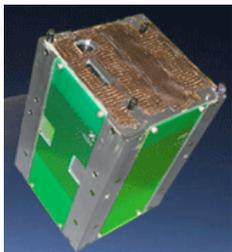
Bandit-C, 3 kg		<ul style="list-style-type: none"> • <i>Primary</i> Proximity operations of a microscale free-flyer relative to a host spacecraft. • <i>Extended</i> Repeatable docking, 6DOF control, visual navigation, autonomous flight. 	Akoya-B, 29 kg		<ul style="list-style-type: none"> • <i>Primary</i> Support Bandit-C. • <i>Secondary</i> Demonstrate RI&T with modularized subsystems, distributed C&DH, and standard power/data protocol.
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Figure 1: The Mission



Utah, in August, 2006. Protoflight units were delivered for Flight Competition Review by NS-4 in Albuquerque, New Mexico, on March 27, 2007. The protoflight spacecraft will be prepared for environmental testing by June, 2007, and ready for launch in August, 2007. ASL/WU is seeking secondary launch for the spacecraft.

MICROSAT ON THE MOVE: BANDIT PROX OPS MISSION

Bandit-C operations incrementally confirm Bandit's activation and readiness, docking ability, 6DOF navigation control, and simple to complex tasking, beginning with the Primary Mission.

The Bandit-C Primary Mission, seen in Figure 2, is to demonstrate proximity operations of a 3 kg free-flying proximity operations vehicle. Mission Success is defined as one release and recapture of one vehicle. Following completion of the Primary Mission, operators will proceed to the Extended Mission, seen in Figure 3. Extended operations demonstrate feasibility of microscale satellites for advanced missions, including repeatable docking, 6DOF relative navigation, image-based position sensing, and ground and autonomous control of a microscale free-flyer:

- **Repeatable Docking:** Bandit self-attaches to Akoya between off-dock flights by contacting a

Velcro docking ball. While docked, Bandit can power down, recharge, dump momentum, and hold position. The Velcro is soft to protect against impact, and reusable for many flights.

- **6DOF Relative Navigation:** Bandit uses blended sensing techniques, including roll rate gyros, one three-axis accelerometer, an infrared range finder, and visual position determination. Combinations of sensors determine attitude, position, and velocity relative to Akoya down to 5 mm/s translation and 0.4°/sec rotation. Bandit is self-propelled in 6DOF with cold-gas thrusters.
- **Image-Based Position Sensing:** Bandit and Akoya process photographs of each other for position determination. Bandit photographs an array of light emitting diodes (LEDs) on Akoya and autonomously determines its pose based on the LED arrangement. Akoya views the Dock to verify docking, and the Earth to verify pointing.
- **Ground and Autonomous Control:** Bandit can be commanded by the Ground or by Akoya's autonomous flight algorithms. Command methods range from direct control of thrusters to waypoint-based guidance to open-ended autonomous tasks such as "return to dock."

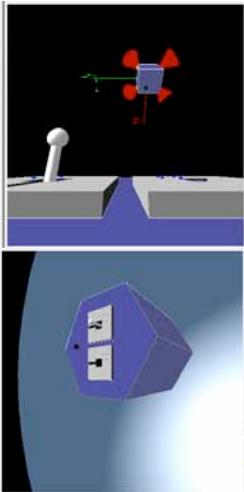
EXTENDED MISSION Operations Plan	<i>Duration: 28 days, longer as systems last.</i>
<u>SIMPLE TASKING</u>	
<p>OBJECTIVE 2: Validate Bandit Design, 7-14 days</p> <ul style="list-style-type: none"> • Activate Bandit-2, confirm communications, and charge. • Confirm proper function of all sensors and actuators while attached to dock. • Perform same and/or extended operations as for Bandit-1. <p>OBJECTIVE 3: Repeatable Docking and 6DOF Control, 7 days</p> <ul style="list-style-type: none"> • Release Bandit, thrust away from dock up to 100 cm, return, and recapture. • Release up to 50 cm, execute roll, pitch, and yaw maneuvers (zeroing motion between each maneuver), return, and recapture. • Release up to 50 cm, thrust along the 1 and 2 axes (where the 3 axis is orthogonal and points into the dock), return, and recapture. 	
<u>COMPLEX TASKING</u>	<p><i>Ground operators use a 6DOF computer simulator to visualize telemetry during Extended Ops. Above: Akoya's view. Below: Bandit's view.</i></p>
<p>OBJECTIVE 4: Inspect and Orbit, 7 days</p> <ul style="list-style-type: none"> • Release up to 100 cm, hold position for 60 seconds, return, and recapture. • Release up to 50 cm, orbit Akoya, return, and recapture. <p>OBJECTIVE 5: Blended Autonomous Operations, 7 days</p> <ul style="list-style-type: none"> • Demonstrate blended autonomous operations, including direct operator control of attitude control actuators, high-level waypoint-based guidance, and open-ended autonomous tasks such as "return to dock." 	

Figure 3: Extended Mission Operations Plan



The missions are enacted via a series of sorties; a sortie is the sequence of actions performed by Bandit-1 from the time it leaves dock until it returns. Basic mission success can be accomplished in two weeks. Extended operations can be performed in 28 days, but will continue as long as the spacecraft are functional.

DOMINATED BY MISSION: PROX OPS DESIGN FEATURES

Bandit houses several specialized proximity operations system elements, including cold-gas thrusters, blended navigation sensing, visual inspection capabilities, and part of the autonomous control processing. These mission-specific components occupy roughly 80% of total volume. The other 20% contains a power board, ten AAA nickel-cadmium batteries, and short-range board-mounted radios and antennas. By distributing long-term power generation, long-range communications, large complex-processing boards, and between-contact position stability to Akoya and the Dock, nearly all of Bandit is dedicated to mission.

Self-propelling 6DOF Thrusters

Bandit is self-propelled in 6DOF by an 8-thruster, multi-phase propulsion system with a supersaturated cold gas propellant, R134a. The propellant tank, valves, and tubing occupy 50% of Bandit's total volume. The propellant tank, seen in Figure 4, is fully integrated into the structure, conserving space.

The tank is filled with R134a through a fill valve. The pressure differential between the internal and external surfaces of the tank causes propellant to flow when valves are opened. Bandit has ten solenoid valves, eight control thrusters for directional

actuation and two isolation valves between the thrusters and tank to prevent leaking. A flow diagram is seen in Figure 4.⁶ Using heaters around the valves, each thruster is expected to deliver at least 20 seconds specific impulse and 50 mN thrust on orbit. The thrusters are arranged such that sets of four provide uncoupled actuation around all six principal translation and rotation axes. Each directional pulse is expected to exert 5 mm/s velocity change.

The tank operates nominally at 90 psi, maximum 250 psi. The design has been hydrostatically verified to leak at 3,150 psi with no potential for catastrophic failure, a factor of safety 12.6 above 250 psi. A relief valve provides additional security against burst.

Bandit-C cannot refuel on orbit; when the propellant is depleted, the mission is over. The greatest constraint on mission life, therefore, is volume, which limits the capacity of the propellant tank. Even at microscale, Bandit is designed to hold 12,000 mm/s velocity change worth of propellant at 90 psi, or 2,400 directional pulses. This is sufficient to complete Extended Operations. Also, Bandit-2 is a complete on-orbit spare. Because the Akoya hub can support multiple payloads, mission redundancy is achieved without the need for multiple monolithic spacecraft and/or launches.

Blended Navigation Sensing

Primary navigation sensing is accomplished through three roll rate gyros and a MEMs three-axis accelerometer. Secondary sensing and position verification is performed by an infrared range finder and image processing.

To maneuver safely within millimeters of another spacecraft, Bandit must be delicately mobile in mini-velocity increments. However, to measure 5 mm/s velocity changes on a 3 kg vehicle, Bandit requires nano-g accelerometer resolution and less than 1 °/sec roll rate resolution for a 600 second sortie. Bandit's roll rate gyros are accurate to 0.4 °/sec, but even the most expensive commercial-grade accelerometers can provide no more than micro-g resolution.

To solve this problem, mission-critical sorties last only a couple minutes (Mission Success requires only ten seconds off-dock). To achieve extended sorties, such as Akoya orbits or position holds, Bandit's slower secondary sensors refresh the inertial

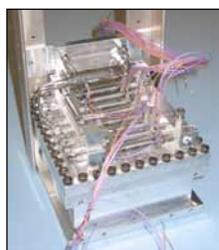
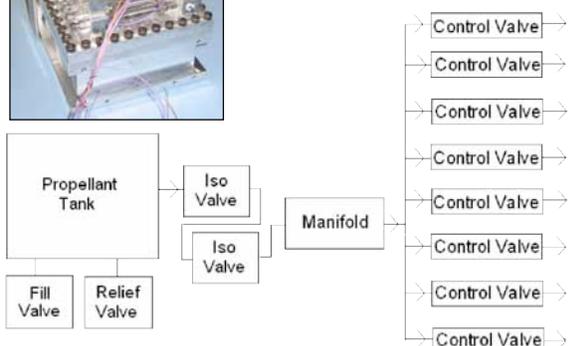


Figure 4: Propulsions system. Left: Propellant tank with valves and wiring. Below: Propellant flow diagram.



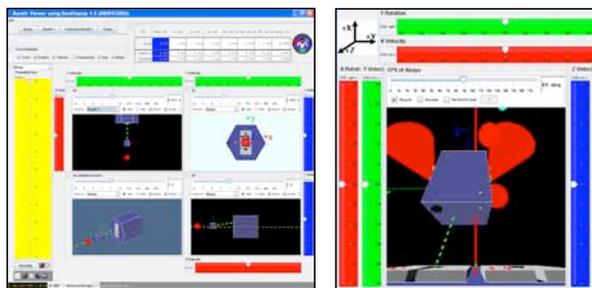


Figure 5: The 6DOF simulator and position estimator shows views from Bandit, Akoya, and a third-person observer.

sensors with a known position and provide visual confirmation of sensor values. Current software provides visual position updates at 1/4 Hz. Software engineers project improvement to 2 Hz before launch.

In addition, all sensor data is visualized in a 6DOF computer simulator on the Ground. The user interface is shown in Figure 5. The simulator accounts for all known disturbances, including orbital drift, spacecraft rotation, and thruster imbalances. It includes a position estimator based on actual or simulated telemetry, and can activate flight algorithms such as “Return to Dock.”⁷ Ground controllers use this interface for stick-level or autonomous commanding.

Visual Inspection

For long-duration, long-range sorties, Bandit utilizes an experimental visual navigation system. Bandit photographs a pattern of LEDs on the surface of Akoya. On-Bandit processing locates the centroid of each LED. The LED positions are relayed to Akoya, which extrapolates relative position. The position refreshes the inertial sensors, and can be used by Ground controllers to command Bandit’s thrusters manually, or by Akoya to command Bandit’s thrusters autonomously.

The LEDs are arranged in squares of four with one “uniqueness” LED within the square that breaks the



Figure 6: Bandit determines position by analyzing photographs of the Akoya LED array. Left: Short-range sorties use a small docking LED set. Right: Long-range sorties use large LED set.

symmetry, as seen in Figure 6. On-board software identifies the LEDs, extrapolates all angles and distances from which the known square would appear as seen, and selects the best possible solution based on the last known position. The uniqueness LED limits the possible choices. One such 2 cm square is next to the docking ball. Bandit hones in here when re-docking. With Bandit’s small camera, the docking LEDs are only distinguishable to about 10 cm. For longer-range sorties, Bandit sees a second 20 cm square on the edges of Akoya. The blended light from the docking LEDs provides the uniqueness point. For orbit sorties, the Earthside face and three alternating sides of Akoya have LED sets. The number of sides with LEDs is limited to decrease the number of LEDs Bandit may see at a time. This avoids confusion and increases processing speed.

Other techniques for visual position reference on larger-scale missions could include line-recognition, three-dimensional shape recognition, or multi-color LEDs to narrow down possible positions. Akoya is equipped with multi-color LEDs in preparation for a future software upgrade.

Autonomous Control

For near-dock sorties, including Mission Success, Bandit’s position and attitude are controlled by an open-loop algorithm that fires thrusters based on a preset timer schedule. Bandit relies on primary sensors. For more complex missions, Bandit flies autonomously. ASL graduate student Jeremy Neubauer won second place in the 2006 SmallSat Student Paper Competition for his development of the autonomous algorithms.⁸ The algorithms utilize a velocity potential function controller, which uses a minimum-seeking method similar to Lyapunov functions. Bandit relies on all sensors and the position estimator of the 6DOF Ground simulation.

FRACTIONATION: SHARING SUBSYSTEMS

Akoya and Bandit share distributed, or fractionated, subsystems. Bandit has limited power, processing, and communications ability to reduce size and cost. It is dependent on Akoya, which provides robust subsystem support (docking, charging, complex processing, and Ground communications) such that maneuverable, expendable Bandit has advanced capability for innovative demonstrations. Bandit is ideal for short- to long-range, short-duration free-flying missions. Stationary, long-duration Akoya is a

platform for multiple Bandits and additional payloads.

Repeatable Soft Docking

The on-orbit dock consists of a retractable arm that moves on linear bearings and is covered with hook-and-loop self-gripping fasteners (Velcro); this offers Bandit a long-term stable platform allowing it to shutdown between sorties. The arm is extended by a linear motion mechanism; Bandit impacts the Velcro, and the arm retracts to pull Bandit in. To release, the arm is retracted to the interior of Akoya, peeling apart the two sides of the Velcro.

The “Velcro ball on a stick” provides exceptional error-tolerance for docking, handling entry angles up to 90° and speeds between 0.1 and 100 cm/s while cushioning impact. A single Velcro hook supports 580 mN, three orders of magnitude margin on the required 0.1 mN, and shows no degradation after one hundred cycles. It is simple, versatile, reliable, and reusable.

Power Charging

To further reduce Bandit’s size and complexity, it is only responsible for short-term power. Bandit actually does not have enough surface area to provide its own power through solar cells. Bandit is battery-powered with ten AAA NiCad cells and recharges through the Dock between Sorties, making use of Akoya’s long-term solar cell/battery combination. Bandit’s battery pack can power all components at 100% duty cycle for thirty minutes; no sortie will last more than eight minutes, the length of a typical contact window.

The Velcro on Bandit and the docking ball is steel and electrically conductive. When docked, Bandit’s small legs rest on the top of Akoya, which is covered in grounding plate. Combined, the Velcro and

grounding connections close a charging circuit that charges Bandit’s batteries when docked, seen in Figure 7. Charging takes about ninety minutes, depending on cell depth of discharge.

Communications Hub

Akoya is the communications relay between Bandit and the Ground. All commands to and telemetry from Bandit pass through Akoya, such that Bandit is free of cumbersome high-power radios and antennas. Commands and telemetry are relayed at 435 MHz between Ground and Akoya, and 418 MHz between Akoya and Bandit. Dedicated video links at 2.4 GHz and 900 MHz connect Ground to Akoya and Akoya to Bandit, respectively. Video/image downlink is not necessary for Mission Success.

Shared Processing

Autonomous control and visual position determination are processed by Akoya on several Atmel Atmega128 microcontrollers. Bandit is only responsible for photographing Akoya, determining LED position, and relaying that information and the raw image to Akoya. Akoya processes the more complex tasks of position extrapolation, autonomous commanding, and image compression. Compressed images are sent to the Ground; position and thruster commands are sent to the Ground and Bandit. Akoya hosts a suite of two AVR-Sat boards, one frame capture board, and a supporting electronics board for these operations, while Bandit only needs to hold two 10 x 10 cm electronics boards. Akoya’s electronics suite is used for both Bandit-1 and Bandit-2.

ALL ABOARD THE BUS:

AKOYA RAPID INTEGRATION

Akoya is a fully-customizable support bus, with modularized plug-and-play subsystems standardized by a common power/data protocol. Its secondary mission is to demonstrate RI&T by exchanging “black box” payloads with SCU and blind-integrating each other’s “black boxes” at a design review. One tray on Akoya will be contain at least one non-WU payload to demonstrate the feasibility of RI&T for space, and verify the Akoya platform as a multi-microscale payload host.

Modularized Subsystems:

Distributed Command and Data Handling

Akoya uses the SCU-designed distributed Command and Data Handling (dCDH) architecture in which each subsystem is controlled by its own Atmel

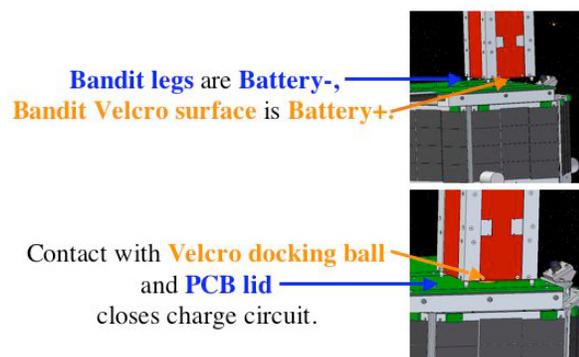


Figure 7: Bandit charges automatically while docked.

Atmega128 microcontroller. Distributed processing makes each subsystem modular for ease of testing, integration, and component swapping on the ground. Elements can be inserted or removed from the system without interfering with the function of other components.

All subsystems send and receive commands based on the Emerald Data Protocol (EDP). The physical message-transmitting layer is the Inter-Integrated Circuit (I²C). To expedite message decoding, header information, such as the source and destination address, is included in every information packet. A typical command is an eight-bit hexadecimal number associated with an ASCII character. A subsystem only reacts to packets with its address.

Because all subsystems conform to the same power/data pin-outs, and no two subsystems depend on each other for functionality, all elements can be tested independently in parallel. This significantly streamlines system integration. Assembly and integration from the first inter-subsystem power connection to complete debugged system lasted only 23 hours. Again, nearly immediate integration. This same technique is used for payloads.

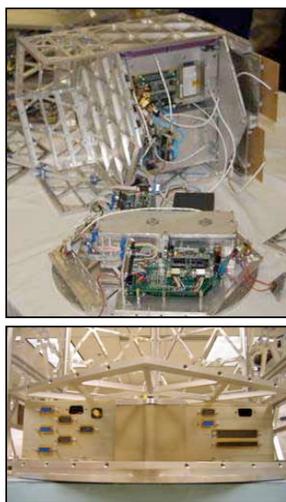


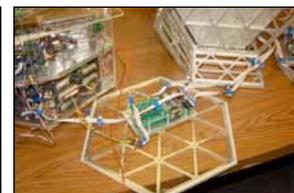
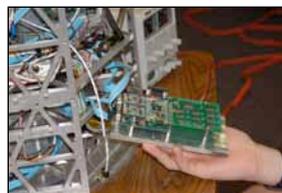
Figure 9: Modularized subsystems can be decoupled from the system without interfering with other functions. Left: Bottom tray slides in and out for debugging. EDU and flight versions. Below: Dock removed for wire harnessing.

Rapid Integration and Test.

The WU team demonstrates RI&T by exchanging “black box” payloads with an external organization. This is a blind integration; beyond establishing a physical footprint, standard pin-out and maximum power consumption, no advance discussion of the components is had. At the meeting, the teams exchange the boxes, integration instructions and a list of commands. The teams then integrate and operate the components without further interaction be-



Figure 10. RI&T SmallSat demo. Left top: Black box exchange. Left bottom: PL fits in allotted volume. Below: Spacecraft merged by connecting wire harnesses.



tween the students. This will be demonstrated both on the ground and for flight.

- **Minimum Success:** Demonstrate data protocol compatibility. The box is connected via the standard data harness in a “flatsat” configuration with its own power source. The device is controlled from the portable ground station.
- **Objective 2:** Demonstrate functional compatibility. The box is powered by the Akoya wire harness.
- **Objective 3:** Demonstrate complete electrical integration with an Akoya Engineering Design Unit (EDU). The box is placed in the unit, connected and operated.
- **Objective 4:** Complete flight integration.

Minimum Success and Objectives 2 and 3 were accomplished with SCU on August 13, 2007 at the 2006 AIAA/USU Conference on Small Satellites in Logan, UT. “Black boxes” were exchanged and interoperated within ten minutes, and the two teams’ spacecraft were completely conjoined in thirty minutes. Having never seen each other’s satellites before, the two teams functionally combined them into one system in half an hour and interoperated from each other’s portable ground station. Photos from the event are shown in Figure 10.

Designed for rapid response plug-and-play, Akoya and Bandit are dynamic systems. Because subsystem modules can be designed, constructed, and tested in parallel with other modules while uncoupled from the system, improvements and swaps are made without impeding integration. With a core team of only 12 students, the fully-functional Akoya EDU and the Bandit structure and electronics were de-



*Figure 11:
2006-2007
leadership team:
5 undergrads,
5 BS-MS dual
degrees, 2 grad
students.*

signed, built, and integrated in three months. In the following nine months, the same students completed the flight Akoya and two flight Bandits. All three spacecraft will begin environmental testing in June, 2007, and will be ready for launch by August, 2007, only one year after flight hardware production began.

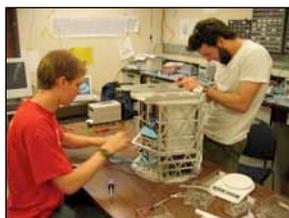
STUDENT-BUILT SATELLITE: CROSS-DISCIPLINE COLLABORATION

Students are directly responsible for all aspects of Bandit/Akoya development: design, fabrication, assembly, integration, test, and management. Over 200 students have been involved since the project began in 2003. The 2006-2007 team, Figure 11, has over 60 participants, led by a core of 12 subsystem leaders, two student Program Managers, and a faculty Principle Investigator.

The program is open to all interested students, and leadership is earned by knowledge, ambition, and enthusiasm, irrespective of class level. Eighty percent of team leaders, including one project manager, are undergraduates or dual degree. Graduate students contribute research in electronics design and Bandit Guidance, Navigation, and Control. In addition, ASL sponsored five high school summer interns in 2006. These students conducted Velcro strength testing, preliminary antenna design, documentation writing, and were involved in fabrication, testing, and integration of a high-altitude balloon demonstration of the Bandit visual navigation system. Of those five students, one submitted a research paper on Velcro strength testing to the Missouri Space Grant Consortium, one returned in



Figure 12: Students are directly responsible for all aspects of development.



March, 2007, to help prepare for the Flight Competition Review, and another is volunteering again in summer, 2007.

Satellite programs offer advanced, multi-discipline applied research to university students, Figure 12. Bandit/Akoya involves students from every discipline in the WU School of Engineering and Applied Science (SEAS), as well as from the School of Arts and Sciences and the Olin School of Business. Engineering students specialize in mechanical, aerospace, electrical, systems, computer science, environmental, and biomedical engineering. Also, students majoring in Spanish, psychology, physics, Earth and planetary sciences, accounting, and business administration are team leaders and significant contributors. ASL bridges the gap between SEAS and other WU departments by collaborating with the Department of Physics on thermal-vacuum testing, the School of Business on marketing, and the Art School on website design and publicity.

In the spirit of cooperation, ASL has formed strong collaborative relationships with other universities, Figure 13, combining skills across the country. For example, WU uses SCU's distributed computing processes, SCU uses the adaptable Akoya structure, and students periodically travel to develop software and exchange hardware. This kind of cooperation is made possible by the Emerald Protocol Standard. ASL is a front-runner in initiating standards and design sharing between universities in the AFRL University Nanosat Program. If implemented, modules from top programs across the country can be combined into single spacecraft. Already, Akoya has a dedicated rapid integration tray for any additional payload conforming to the standard. Combining the best of the best of university subsystems may significantly advance the potential of student small satellites.



Figure 13: WU combines resources with SCU. Left: High-altitude balloon test flight. Right: RI&T demo at 2006 SmallSat.

CONCLUSION

Bandit/Akoya optimizes the limited volume of microscale satellites by distributing long-term func-

tions to a nanosatellite host. By fractionating power, processing, communications, and position maintenance (docking) to Akoya, Bandit has the capacity for mission-specific subsystems.

At only 3 kg, Bandit is uniquely capable of advanced demonstrations: proximity operations within centimeters of another spacecraft, repeatable docking, visual navigation, and autonomous control. Each Bandit can be manufactured for \$15,000 using commercial off-the-shelf (COTS) parts, making it a rapidly produceable, appropriate payload for Akoya's plug-and-play architecture.

Akoya's distributed processing and standard power/data protocol give it fluid adaptability to subsystem improvements and payload additions. It is a support hub for multiple microscale payloads. Two Bandits and an additional module are hosted by Akoya simultaneously, empowering many demonstrations at the cost and scale of one nanosatellite - 35 kg and \$70,000 total.

Distributed subsystems and standardization can be used to optimize the small satellite platform for compelling technology demonstrations, including proximity operations and rapid integration, at a fraction of the cost and time of large-scale spacecraft.

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