S4 2020 - PocketQubes are the New CanSats

Technology and Program Overview

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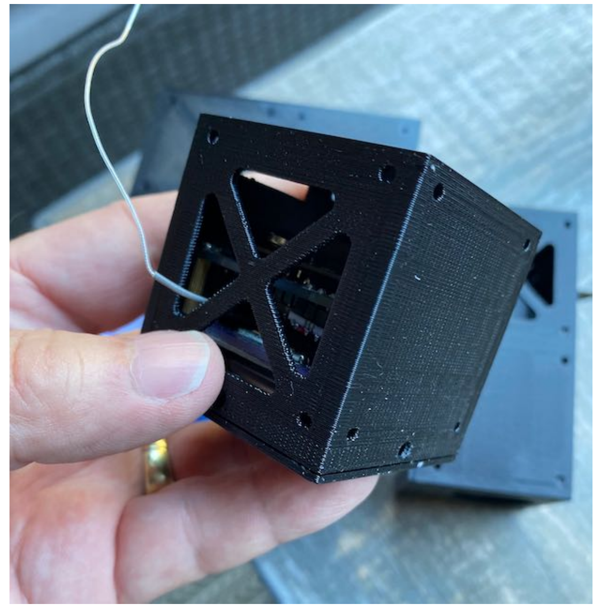

Twenty years ago Prof. Bob Twiggs revolutionized aerospace education by launching small satellites the size of soft drink cans on amateur rockets to short circuit the satellite development cycle. In a heartbeat, these CanSats morphed into CubeSats (10 cm cubes) leading the way for Moore's Law to drop the cost of satellite access to LEO. My colleagues at the AeroPac rocket club in California, colleagues at the University of Tokyo led by Prof. Shinichi Nakasuka and Stanford University led by Prof. Twiggs created ARLISS - A Rocket Launch for International Student Satellites - in the Black Rock Desert of Nevada in 1999. The world's first CanSat launch.

Ten years later, Prof. Twiggs created PocketQubes (5 cm cubes), downsizing CubeSats by almost a factor of 10, changing the scale factor of small satellites again. And the opportunity for changing the paradigm for aerospace education and the satellite development cycle yet again.

PocketQubes are the new CanSats … and S4 (Small Satellites for Secondary Students) is the program to create that new baseline of small, low cost, open source educational satellites on sounding rockets and HABs that lead the way to small satellites in space. S4 was originally a 2014 NASA funded, Sonoma State University (led by Dr. Lynn Cominsky) executed, program for secondary students based on the ARLISS idea of small educational sub-orbital satellites. S4 in 2020, now as an AeroPac/ARLISS program, has adopted the PocketQube form factor to not only replace CanSats for use in student missions on rockets and HABs but also to aspirationally plan for LEO missions. Open source, 3D printed - it is available to all as a baseline to create a new platform for aerospace education.

And perhaps help open space to a whole new generation.

Background

The S4 (Small Satellites for Secondary Students) student satellite system is an opportunity to do science experiments as rocket and balloon payloads targeted to middle and high school students - but also useful to a much wider range of curious learners. It is based on over 20 years of the international ARLISS[2] program of

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[1] Thanks to Paul Hopkins for his collaboration on the 3D printed packages.

[2] A Rocket Launch for International Student Satellites is an international high school and university competition for autonomous robotic student satellites held for the last 20 years by the AeroPac rocketry club at Black Rock Nevada in collaboration with UNISEC-Global - the worldwide university space engineering university consortium. www.arliss.org. UNISEC-GLOBAL.
https://www.dropbox.com/s/dc0szess4adhzig/Sport%20Rocketry%20ARLISS%201.2014.pdf?dl=0

university and high school student payloads that invented CanSats[3], CubeSats[4] and autonomous recovery satellite robots. It uses the PocketQube[5] format for small satellites that is the inevitable successor to CubeSats and CanSats via Moore's Law. S4 began in 2014[6] with the work of Dr. Lynn Cominsky of Sonoma State University, funded by NASA, in collaboration with AeroPac, creating science curriculum extending the ARLISS[7] concept of science rocket payloads to secondary students. The NASA sponsored Rising Data[8] program extended the concept to STEM training for community college students.

The S4 vision is to imagine a progression of science experiments rooted in missions on the ground or on small rockets such as TARC[9], progressing to missions to a few thousand meters on high power hobby rockets (like ARLISS), extending to sounding rocket or high altitude balloon missions to tens of kilometers high in stratosphere and exosphere (like ARLISS Extreme[10]) and eventually to PocketQube missions deployed into Low Earth Orbit. Each step challenges student imagination and abilities with an incremental increase in scope, risk and cost - based on a common platform.

The wide range of sensors and extensibility of the S4 system allow for missions in the atmosphere or the ground (and eventually space!) that are largely only limited by the learner's imagination and are tantalizing close to the capabilities of Star Trek's tricorder.

- Atmosphere science measuring aerosols, dust, radioactive residue, organic compounds, lightning, temperature, pressure, humidity, gas content;
- Measurement of ground and vegetation using visible and infrared light imaging and image processing;
- Vehicle dynamics measuring drag, vehicle orientation, position, trajectory using GPS, accelerometers, gyros, magnetometers, temperature sensors;
- Airframe control for recovery thru servos and/or pyrotechnics;
- Satellite recovery after apogee deployment[11] via parachute or mechanically actuated recovery like steerable parasails or parawings with autonomous guidance;
- Cosmic gamma ray spectrometer analysis in the exosphere. Gamma ray spectrometer analysis as rockets and balloons pass thru the jet stream.

Each 2020 S4 satellite payload is inspired by the new standard PocketQube picosatellite format (in the 1p format, 5x5x5 cm and ~100gm, and in a 2p format - 5x5x10 cm and ~200gm) - invented by Professor Bob Twiggs, inventor of CanSats and co-inventor of CubeSats. Each S4 satellite contains a portfolio of sensors and is programmed as an advanced Internet of Things Cortex ARM computer. Configurations with minimal sensors can be as inexpensive as $50, and full-up configurations with multiple sensors and telemetry can reach over $300. Core data collection loops can exceed 20 Hz, with multi sensor collection loops delivering 5

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3 https://en.wikipedia.org/wiki/CanSat

4 https://en.wikipedia.org/wiki/CubeSat

5 PocketQubes are the successor to CubeSats designed by Professor Bob Twiggs, co-inventor of CubeSats and CanSats. CubeSats are now the standard for modern small satellites - educational, commercial and government. PocketQubes reduce size and weight - reducing the characteristic dimension from 10 cm to 5 cm - recognizing the increase in electronics density of Moore's Law. A number are now in orbit with more on the way. https://en.wikipedia.org/wiki/PocketQube

6 https://www.dropbox.com/s/10g3w2qxc5axnbo/S4%20Student%20Satellite.pdf?dl=0

7 ARLISS - A Rocket Launch for International Student Satellites. www.arliss.org

8 http://lbym.sonoma.edu/RisingData/user/register

9 Team America Rocketry Competition (www.rocketcontest.org) lofting raw egg payloads on mid-power rockets using E thru G motors.

10 ARLISS Extreme is a two-stage amateur sounding rocket that can take 600g of PocketQube payload to 40+km on commercial motors as an FAA Class II rocket. https://www.dropbox.com/s/3oml83hwd5okfgd/AeroPac2012100kProgramReport.pdf?dl=0

11 Standard ARLISS CanSat deployment.

Hz.   Future ARM processor enhancements and improved I/O bus rates can imagine higher sensor speeds and multiprocessor configurations.

Each S4 satellite is configured in a 3D printed package (usually ABS).

S4 collects data locally on the satellite in non-volatile flash memory and/or micro-SD card.   S4 payloads can add real time radio telemetry using modern spread spectrum long range radio communications to communicate to ground stations and download real-time telemetry from the mission and track payloads via GPS.   They can communicate locally at high speed via peer-to-peer WiFi.

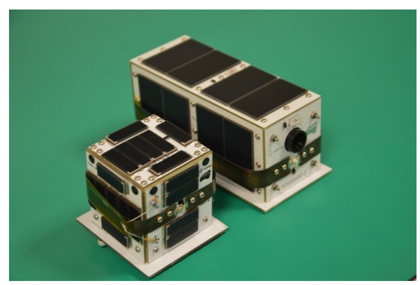
The system is extensible and new sensors can be added to each S4 satellite for new and different missions. Users can make use of the default sensors and mission programming or add new sensors and programming.

S4 satellites are designed to be flown on rockets as small as TARC size rockets or drones that fly a 1p S4 payload on E and G motors to 1000' up to high power sounding rockets or balloons that reach the top of the stratosphere. S4 satellites can be configured for either captive flights[12] or to be deployed at apogee on a recovery device (such as a parachute) for independent recovery and descent[13].   The 3D printed PocketQube format allows for an incremental transition to an ultimate space capable packaging suitable for LEO deployment.

S4 changes the scale of small student payloads. Because we can now fly many more satellites per airframe, we dramatically reduce the cost of each mission - dividing the recurring cost of the motor by the number of satellites.   In large ARLISS M configurations, this is almost a 20x reduction in per mission cost!   But with single payload missions on mid-power rockets, introductory missions to 1k+ are are reduced in cost to small 10s of dollars, using carrier rockets largely 3D printed.

The S4 program anticipates rapid technology changes in platforms and sensors and has tried to standardize on common standards for programming language, packaging, communications and sensor interfaces.

Multiple PocketQubes have successfully been deployed to LEO, beginning with the 2P $50Sat[14] in 2013 that pioneered single chip FSK radios.   In November 2019, the 1P FOSSASat developed by high school students in Spain, reached LEO and successfully demonstrated single chip LoRa/RTTY spread spectrum radio communication to ground.



Missions

Science is about the journey of iteratively asking and answering questions about the world we live in.   S4 is such a tool to ask questions about the earth and the space the around it using rockets and high altitude balloons as interesting platforms to observe.   They provide opportunities to investigate second hand (by our robots and their sensors) deep questions about the earth and its environment.

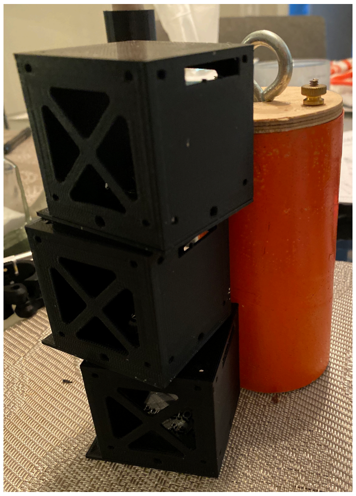
S4 leverages four amazing recent innovations in citizen science:

- Low cost sounding rockets and high altitude balloons,

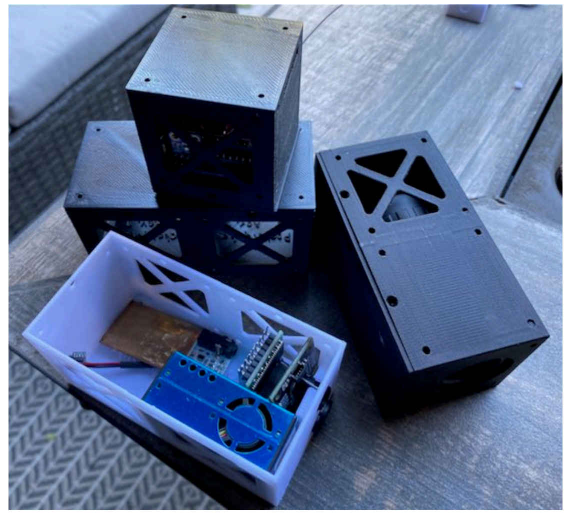
[12] To be recovered with the rocket or ballon that launched them.

[13] Standard ARLISS CanSat deployment - independent PocketQube recovery under parachute, parawing or … whatever.

[14] http://50dollarsat.info



•Robots and low cost environmental sensors,
•3D printing of both packages and airframes,
•Internet and data sharing.



S4 is a modular set of tools allowing a range of science missions in different S4 configurations - ranging from a simple one like a 1P PocketQube at low altitude, and a more complex 2P PocketQube to the stratosphere. Different sensor suites might be better suited for younger learners and simpler missions (say middle school) while missions with spectrometers and GPS might be better suited for more sophisticated learners and more complex missions (say advanced high school). In the picture to the right, we can see four configurations of S4: a basic 1P sitting on 2P package, a 2P configured with a gamma radiation sensor, a particulate matter spectrometer, a video camera and IR imager, and a 2P configured with a small telescope with video camera. As we can see on the left, three 1P satellites can fit in the space previously taken by one classic CanSat.

Since S4 is in the standard PocketQube format we can imagine, with appropriate modifications, extending these missions to LEO.

An S4 PocketQube has a rich portfolio of (optionally) configured sensors with most data sampled at 10 Hz:

- GPS position of latitude, longitude and altitude (to 80 km),
- GPS time,
- Battery voltage,
- Mission time to the millisecond,
- Temperature - both internally to the S4 but also to two external 1-Wire based temperature sensors
- Humidity,
- Air pressure,
- eCO2,
- TVOC - including carbon monoxide
- 3x accelerometer,
- 3x gyroscope,
- 3x magnetometer,
- UV, visible and IR light intensity
- Particulate matter spectrometer(PM1.0, PM2.5, PM5.0) (particle density: .3u, .5u, 1u, 2.5u, 5u, 10u) (1 Hz)
- AS7265 18 channel 410-940 nm near-UV to near-IR light spectrometer
- Beta, x-ray and gamma radiation spectrometer < 1 MeV
- 32x24 pixel 60 degree infrared imaging sensor,
- Visible light imaging camera (optionally removable IR filter for multispectral imaging)[15].

It is configured as a 3D printed ABS 50mm 1p (or 1.5p or 2p) package for either captive flight or independent deployment for parachute recovery. It weights about ~50-200 grams depending on sensor configuration. Spread spectrum wireless telemetry allows for independent tracked recovery. Additional sensors can be configured on standard extension busses (I2C, serial, 1-Wire, SPI, DIO). Open source data collection and telemetry software is Arduino/C++ based.

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[15] https://publiclab.org/notes/warren/12-10-2010/normalized-difference-vegetation-index-nrg-and-landsat-7-bands

Some Simple Missions

Simple S4 missions are based on questions suitable for middle school science.

Question	Sensor(s)	Study Guide
How do we determine altitude from pressure in the atmosphere? What IS the atmosphere?	Barometer Temperature	Atmosphere
What is humidity? How does water content in the atmosphere change with altitude? Time of year? Location?	Barometer Humidity Temperature	Atmosphere
How does CO2 in atmosphere change with altitude? Time of year? Location? Vegetation?	Barometer Humidity Temperature	Atmosphere
How does pollution from TVOCs change with altitude? Location? Adjacent sources of pollution? What ARE TVOCs? Time of year?	Barometer TVOC	Pollution Organic compounds
How are any of the above related to temperature? To each other?	Temperature	Weather
How do answers to any of the questions change in different locations or at different times or seasons.		Weather
How fast did the rocket go?	Barometer	Physics Atmosphere
How high did the rocket go?	Barometer	Physics Atmosphere

More Complex Missions

A rocket based mission to 30k' can take advantage of the rich portfolio of S4's sensors to ask many more questions. Such a flight will be supersonic and will pass from the troposphere into the lower edge of the stratosphere, and likely into the jet stream (depending on jet stream and location). On such a flight several S4s could be flown and multiple questions could be flown from multiple sensors on different subjects.

Question	**Sensor**	**Study Guide**
How fast and high? Do GPS and barometer agree?	GPS Barometer	Physics Atmosphere
What was the path of the rocket flight?	GPS	Physics Mapping/visualization
What did the airframe experience? Stress? Temperature? Acceleration?	IMU Temperature GPS	Aerodynamics Strength of materials Physics of rocket flight
What were the physics of the rocket's flight. How much drag was on the rocket. How could you measure it? Did it change with altitude? How?	IMU Barometer Temperature	Aerodynamics Physics Atmosphere
How much energy did the rocket motor put out?	IMU GPS	Design of rocket motors. Chemistry Physics of rocket motors

What did the atmosphere look like during the rocket's flight? What did it consist of? How did it change? Why?	Barometer Temperature Humidity Particulate matter TVOC CO eCO2 Radiation	Composition of the atmosphere How sensors work Aerosols
Did the rocket enter the jet stream? Stratosphere? How could you tell?	GPS Barometer Temperature Pressure	Composition of the atmosphere Jet stream
Does light change with altitude? Why?	Spectrograph GPS Humidity Temperature Particulate matter IMU	Light and atmosphere Light propogation
Is the sky blue? Why? Why not?	Spectrograph Humidity Particulate matter	Physics Atmosphere
Did the rocket find air pollution? What. Why. Where.	Barometer Humidity TVOC Particulate matter Radiation eCO2 CO Pressure Spectrograph	Air pollution Aerosols TVOC CO
Did the rocket see radiation? If so, where could it come from? What kind?	Radiation sensor Particulate matter Humidity Pressure GPS Barometer	Radiation aerosols Nuclear physics Nuclear testing Nuclear plant failures Atmosphere science
Can we detect vegetation and changes with vegetation with season and water content?		

Mission Software

S4 is based a common satellite mission software package that includes:

- Management drivers for each sensor to initialize and collect data from each sensor;
- Communications protocols for location telemetry to the ground;
- Data collection loop that
  - polls configured sensors,
  - periodically saves sensor data to local flash storage,
  - wirelessly transmits location data to the ground station,
- Ground station software to receive location telemetry from mission satellites.
- A portable Python desktop/laptop dashboard downloads mission data from the satellite and displays.

This package is written in C/C++ and is hosted on the standard Arduino IDE.

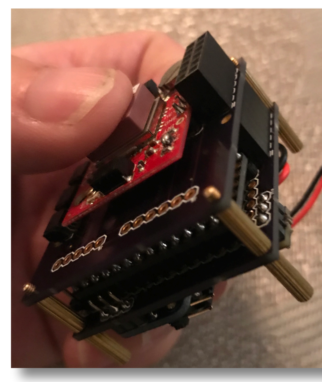
The S4 hardware also supports Python for users that prefer to port the mission software to that environment.

The S4 mission software is open source and available for modification and improvement.

S4 Hardware Platform

S4 provides a standard modular platform to accommodate different missions. All platforms are powered by a 3.7V LiPo battery sized for the mission and configuration. Small configurations are powered by as little as 100 mAh, while more robust configurations require 350+ mAh, delivering hours of operation.

Platform	Package	Processor	Data Storage	Communications	Sensor Capacity	Scope
S4	1p, 1.5p, 2p PocketQube, 3D printed ABS plastic	ARM Cortex M0 or M4 C/C++	22 MB Flash, microSD card	LoRa telemetry	< 10	Standard Arduino platform with local storage, telemetry and substantial sensor capacity.

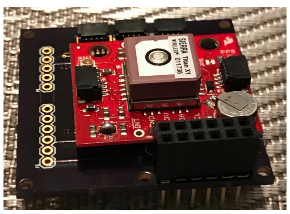
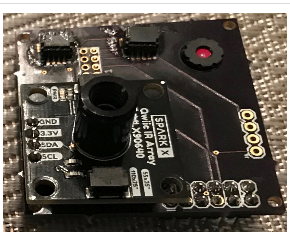


S4 is based on an enhanced processor platform - the ARM Cortex M4 - the Adafruit ItsyBitsy M4 Express. It adds the baseline S4 sensors: flight capable GPS (capable to 80 km altitude), 3d accelerometer, 3d gyro, 3d magnetometer, temperature, atmospheric pressure, battery voltage, equivalent CO^2 concentration, TVOC, humidity, UV+IR+visible light intensity, and an 18 channel light spectrometer from 410-940 nm. The board flash mission memory expands to 22 MB for local recording of sensor data and a LoRa wireless data connection provides for real-time tracking and telemetry. The platform includes a serial port, a digital/analog port and an I2C port for sensor expansion. It is programmed with the Arduino IDE and the standard S4 mission software.

The S4 is based on the standard PocketQube 42mm square stackable boards with a common inter-board communications and power bus. The basic S4Qube can be assembled from two boards - the Processor, Memory and Telemetry Board and the Sensor Board - outfitted with a set of commercially available daughterboard sensors designed for the science mission in mind.

There is room for one or more boards of standard PocketQube size within the S4 1p package depending of component height. Such boards could contain additional sensors or perhaps stepper motors to control a deployable parawing for a controlled, steerable recovery. An example of such a board could contain the interesting the AS3935 lightning sensor for mapping distance to storm fronts at altitude.

Some sensors - like the imaging sensor, the particulate matter sensor, the multispectral imaging sensors or the radiation sensor can be packaged in a 2p configuration.

	S4 Processor, Memory, Telemetry Board	Custom, open source	
	120 MHz Cortex M4 w/ hardware floating point processor, 512k program flash, 192k SRAM, I/O, 2 MB flash memory mission storage	https://www.adafruit.com/product/3800	$14.95
	LoRa telemetry radio	SPI, u.FL antenna	
	20 MB expanded mission memory	SPI	
	LiPo battery + management	Solar cell recharging	
	Connectors	1Wire bus S4 Power S4 bus	
	S4 Sensor Board	Custom, open source	~$3
	Sensors	I2C Mediatek GPS, I2C VEML6070 UV sensor, I2C visible + IR sensor, I2C spectrometer, I2C eCO2+TVOC+temperature+pressure+humidity, I2C acceleration+rotation+magnetometer, I2C MSLaltitude Particulate matter PMS- 5003 spectrometer is connected on a QWIIC serial port. Gamma ray X100-7 radiation spectrometer is connected on a QWIIC DIO port.	
	Connectors	QWIIC I2C, Serial, DIO S4 Bus	
	S4 Imaging Board (Experimental)	Custom, open source	~$3
	Sensors	640x480 false color serial .jpeg Thermal 32x24 image	
	Connectors	QWIIC I2C, Serial S4 Bus	
	3D printed 1p and 1.5p PocketQube enclosures	To be published	~$3

The third board - the Imaging Board - is experimental. It integrates two imaging sensors to investigate multispectral imaging. The first sensor is a simple visible light sensor with the color filters changed to allow capture of the near-infrared. This allows assessment of ability of plants to process sugar. The second sensor is a thermal imaging camera. The board allows for the optional integration of an additional light spectrometer for experiments in ground imaging for vegetation analysis.

Type	Pins
Serial	3.3v, Tx, Rx, GND
I2C	3.3v, SDA, SCL, GND
SPI	
Digital/Analog (D/A)	3.3v, Digital I/O, Analog I/O/PWM, GND

Both the Imaging Board and the particulate matter sensor are designed to mounted to the aft outer side of the 1P package to face downward as S4 is deployed for parachute or parawing recovery.

The S4 package is a 3D printed 5x5x5 cm plastic enclosure designed to hold the core processor+memory, baseline sensors, battery, antennas, and additional sensors.

The core S4 electronics are expected to space capable for short missions to LEO. It is anticipated that the plastic PocketQube form factor can be upgraded to WindForm - a 3D printed space capable material and format[16].

Standard Expansion Interface

S4 defines four external sensor interfaces, each defined a simple four wire interface using SparkFun's QWiiC[17] 4 pin connector, providing power and data interfaces from sensors to the processor. SparkFun uses QWiiC just for I2C, but S4 extends it to add a serial port as well as a digital/analog port but adopting a common common miniaturized polarized connector. Standard Arduino C/C++ sensor libraries are used in the S4 Mission Software.

All of the S4 platforms also support an internal SPI peripheral interface, generally limited to communications and internal storage peripherals and not generally supported as an external sensor interface.

Sensors

The S4 system uses an open ended collection of sensors, on standard hardware interfaces, to measure position, light, dust, chemistry, atmosphere, radiation and multispectral imaging.

The following table represents sensors that can fit in the package, have supported drivers, and are believed to collect useful data during rocket or balloon flight. Tested drivers for these are contained in the S4 Mission Software.

The list is under continual review as flight experience is accumulated and as new sensors are available and missions are imagined.

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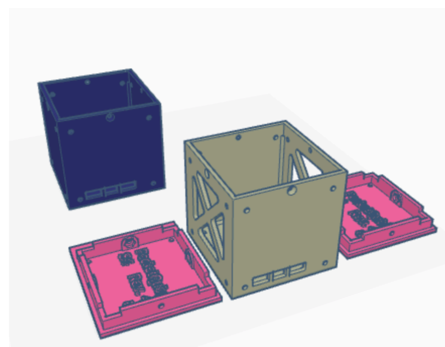
[16] Windform has already been flown in LEO. http://www.windform.com

[17] https://www.sparkfun.com/qwiic

Measurement	Sensor	Description/Link	S4Qube s	o
Time	Mediatek XA110 GPS	.5 sec with 2 Hz refresh rate. https://www.sparkfun.com/products/14414	√	
Location	Mediatek XA110 GPS	3m RMS horizontal precision. https://www.sparkfun.com/products/14414	√	
Geometric Altitude	Mediatek XA110 GPS	10m RMS vertical precision. https://www.sparkfun.com/products/14414	√	
Ambient atmospheric pressure	Measurement Specialties MS5611	Rated to 0 Pa pressure. Over 100k' MSL altitude https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	√	
	Bosch BME280	30,000Pa to 110,000Pa ~30k' MSL altitude https://www.tindie.com/products/onehorse/air-quality-sensors/	√	
Ambient atmospheric temperature	Measurement Specialties MS5611	https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	√	
	Bosch BME280	-40C to 85C https://www.tindie.com/products/onehorse/air-quality-sensors/	√	
	Microchip MCP9808	High precision external temperature https://www.adafruit.com/product/1782		√
Acceleration	ST LSM9DS1	3D acceleration sensor. Up to 16gs. Software absolute position: roll, pitch, yaw. https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	√	
Magnetic field	ST LSM9DS1	3D magnetic field sensor. Software absolute position: roll, pitch, yaw. https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	√	
Rotation	ST LSM9DS1	3D gyro, rotation sensor. Software absolute position: roll, pitch, yaw. https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	√	
Ambient IR light	AMS-TAOS TSL2591	https://www.adafruit.com/product/1980		√
Ambient Visible light	AMS-TAOS TSL2591	https://www.adafruit.com/product/1980		√
Ambient UV llght	Vishay VEML6070	https://www.adafruit.com/product/2899	√	
CO^2	AMS CSS811	Equivalent CO^2 detector - 400-8192 ppm https://www.tindie.com/products/onehorse/air-quality-sensors/	√	
TVOC	AMS CSS811	Volatile organic compounds - 0-1187 ppb. Ethane, propane, formaldahyde, others https://www.tindie.com/products/onehorse/air-quality-sensors/	√	
Humidity	Bosch BME280	0 - 100% RH, =-3% from 20-80% https://www.tindie.com/products/onehorse/air-quality-sensors/	√	
Lightning	AS3935	https://www.sparkfun.com/products/15276		√

Measurement	Sensor	Description/Link	S4Qube	
			s	o
Spectrometer	AS7265X	18 channel 410-940nm spectrometer https://www.tindie.com/products/onehorse/compact-as7265x-spectrometer/	√	
Temperature	DS18B20 1-Wire Temp Sensor	Two remote sensors available.		√
	Bosch BME280	40C to 85C https://www.tindie.com/products/onehorse/air-quality-sensors/	√	
Camera	Still camera	640x480 still camera. TTL serial interface. https://www.adafruit.com/product/1386 Updated with false color - https://publiclab.org/wiki/near-infrared-camera		√
Particulate matter	PMS 5003	Optical laser dust sensor from .3 micron to 10 micron. https://www.adafruit.com/product/3686		√
Gamma Radiation	First Sensor X100-7	PIN silicon photodiode radiation detector. Detects 0.002-1.0 MeV gamma and X-rays. Detects photon energy. Gamma ray spectrometer https://www.sparkfun.com/products/14209		√
IR imaging sensor	MLX 90640	32x24 array of IR sensors for IR imaging. 55 degree FOV https://www.sparkfun.com/products/14844		√

Package



S4 has a physical package in nominal 50mm PocketQube format supporting standard 42mm PCBs. It can be extended to 2P and 3P configurations. It is nominally 3D printed in ABS for most missions. With a digital design, details can changed for a specific mission.

The S4 system adds lower power rocket solution with largely 3D printed parts for nosecone payload shrouds, fin cans, motor retention and recovery retention.

Communications and Telemetry

An emerging wireless standard for the Internet of things, LoRa[18], is used as the S4 basis for inexpensive, long range, low power S4 telemetry service in either the 430-480 MHz or 902-928 MHz bands in the Americas. LoRa is based on a direct sequence spread spectrum modulation system that provides up to 30 dB of additional radio link budget depending on desired throughput vs range performance.

The LoRa radio link can be uniquely software configured to trade off range vs throughput. Low data rate communication to LEO has been demonstrated. Telemetry speeds range from 100s of b/s ranging to 10s of kb/s are possible with tradeoffs to range. S4 uses the standard RadioHead[19] Arduino communications library to provide the basic protocol structure.

[18] https://www.lora-alliance.org/What-Is-LoRa/Technology

[19] http://www.airspayce.com/mikem/arduino/RadioHead/

The basic S4 ground station is an S4 PocketQube with minimal sensors (just a GPS), attached via a USB cable to a host computer forwarding received telemetry to the host. The ground station connects to a USB port on a local laptop for a .csv telemetry data stream. It has a local I2C OLED showing distance and direction to the payload as well forwarding telemetry to host computer for storage.

Mission Modes

S4 can be flown in a range of vehicles, ranging from small mid-power rockets, to high power sounding rockets to high altitude balloons and aspirationally to LEO. These vehicles deliver mission profiles that work in a local park under 1500' to sounding rocket missions at Black Rock or SpacePort America in the continental US.

3D printing allows us to design aerodynamically efficient airframes that get the most altitude for the least motor power - and the money to pay for propellant. Driving the cost down is a good thing.

Captive and Deployed

S4 missions anticipate both captive and deployed S4 satellites. Smaller missions carry one 1P satellite, large airframes can carry up to 18 1P or the equivalent.

Captive satellites remain within the launch vehicle and rely on the launch vehicle's recovery mechanism for safe return. It is anticipated that the launch vehicle will provide means for access to the external world (air vents, imaging windows, etc) sufficient for the missions of the captive payload satellites.

Deployed satellites are deployed right after launch vehicle apogee in the classic ARLISS manner, and deploy their own recovery and descent mechanism. This mechanism can be a wide variety of safe mechanism - some passive like parachutes or streamers, some active like parawings.

Park Mission

A park mission is envisioned as a captive S4 flight flown on a mid-power airframe on an E thru G motor to 1-2k' AGL. Archetypal 24mm and 29mm airframes have been designed and tested for these missions. Each of these airframes uses 3D printed parts for a nosecone payload carrier, fin can, fly away launch assembly, motor retainer and recovery anchor. The baseline 24mm airframe is anticipated to use chemical motor delay, while the 29mm uses off-the-shelf commercial avionics for deployment. Both flight regimes are subsonic and the rocket planforms are optimized for subsonic drag.

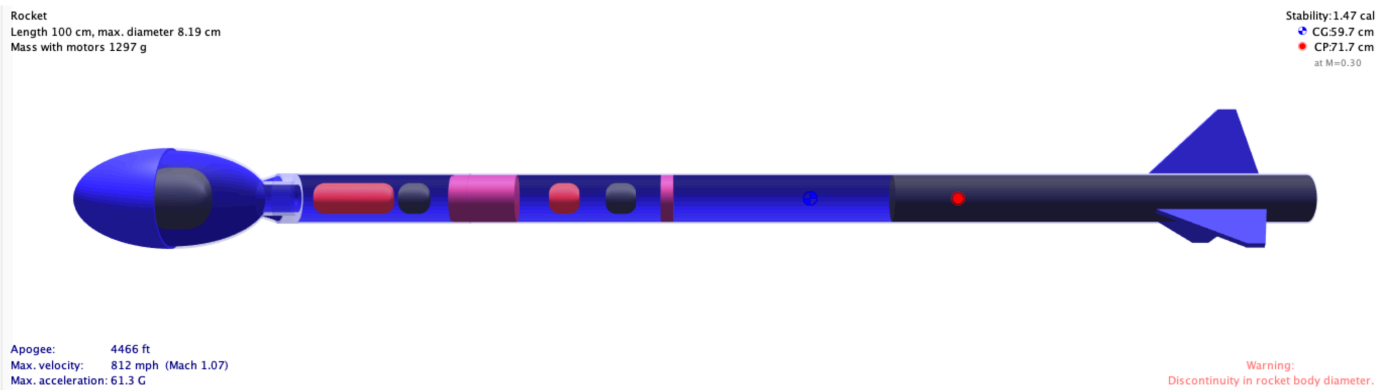
The 24mm airframe can carry a nominal 1P S4 PocketQube to ~750'AGL on E30 or ~1000 on an F24 motor. The 29mm airframe can carry a nominal 1P S4 PocketQube to ~1500'AGL on an F50 to ~3000'+ AGL on an I200.

Small Sounding Rocket Mission

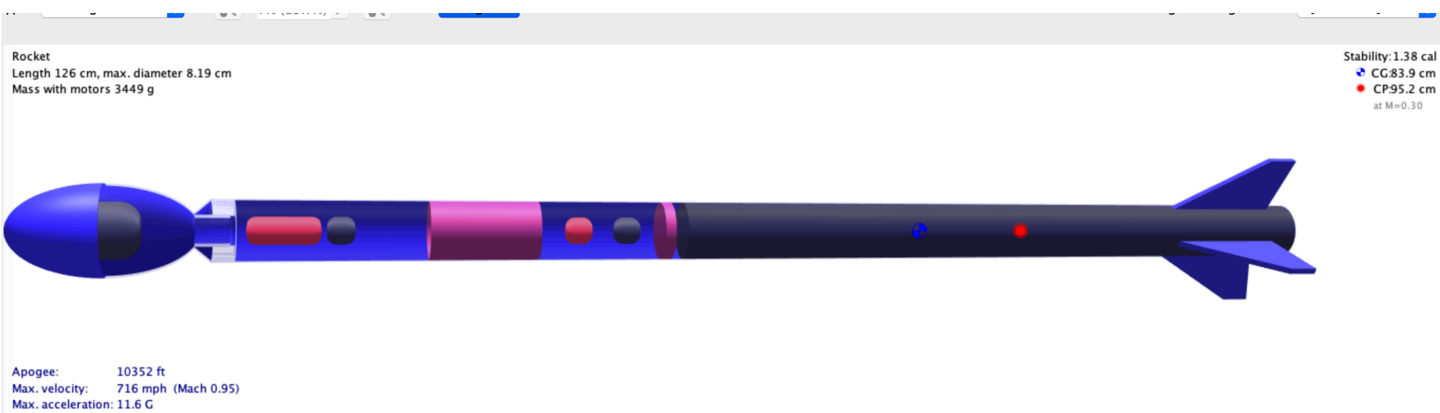
A small sounding rocket mission captive carries a single S4 satellite payload altitudes under 10k' AGL. Much real science can be done in this domain, particularly on the atmosphere and ground imaging as well as supersonic flight dynamics.

Two archetypal airframes have been designed and tested both using the same payload nosecone and upgraded versions of the fly away launch system. Both use avionics for recovery. With this nosecone shape both are high drag and the flight regime is large subsonic.

The 38mm airframe can captive carry a 1P S4 to ~2000' AGL on a G80 up to ~5000' AGL on a J570.



The 54 mm airframe can captive carry a 1P S4 to ~2500' AGL on an I200, and reach as far as ~10k' AGL on a K250.

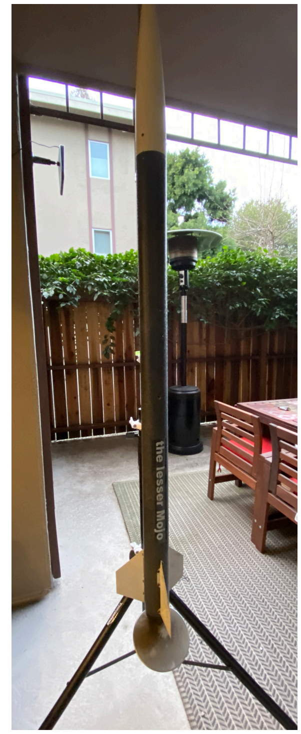


ARLISS K Mission

ARLISS K is one of the two workhorse rocket designs for the ARLISS program. There are variants, the specific airframe depicted is the author's version - customized for S4 missions. An ARLISS K, regardless of individual variance, is always an airframe with a 12" 75mm payload bay - originally designed for one CanSat - in an airframe with a 54mm motor mount. The original ARLISS K CanSat mission profile was carry one CanSat to ~9k' AGL on a K550 motor, deploy just after apogee for the satellite to go on with its mission. At current motor prices, the cost of one mission is the cost of one K550 - about $130.

This ARLISS K, optimized for S4 satellites can carry up three 1P satellites for apogee deployment and two more in a nosecone payload bay for captive carry.

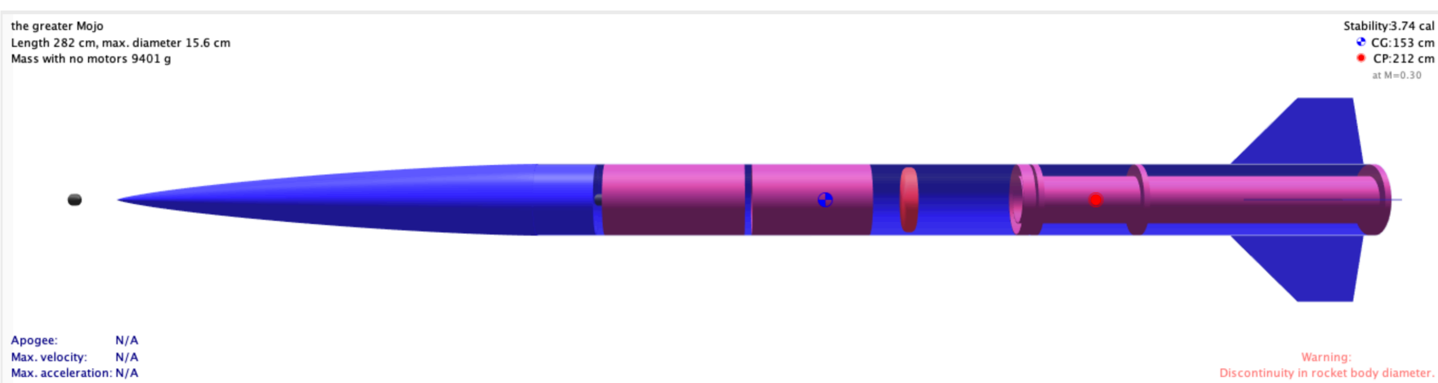
This updated S4 ARLISS K reduces the cost of each mission by 5x - to about $25/S4 satellite.



ARLISS M Mission

The ARLISS M airframe has become the workhorse of the ARLISS program. Originally designed to carry 3 standard CanSats in its 12”x6” payload carrier, to be deployed just after apogee, the most popular mission today is to carry one “unlimited” < 1Kg satellite - generally a ComeBack[20] robot to a target 11k’ AGL.

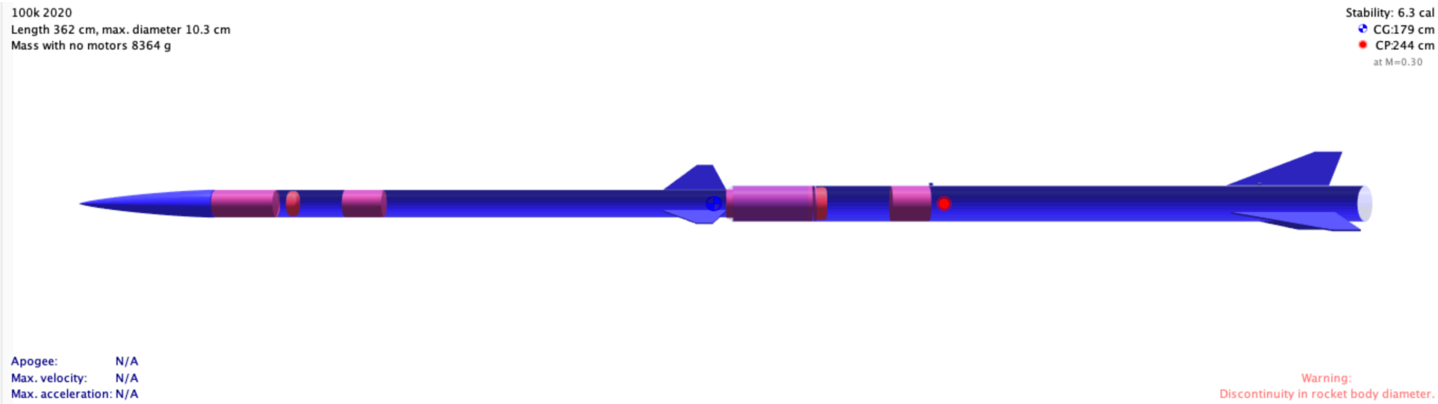
When used for S4 payloads, up to 24P of S4 satellites can be carried between the primary payload carrier, and the nosecone payload bay. These are some mix of both captive and deployable and in a mix of sizes - 1P, 2P and 3P. The more deployable are carried, the fewer satellites can be carried leaving room for recovery gear. Both payload bays have 3D printed inserts specially designed for S4. With 24 satellites, the cost per mission for the typical M1419 motor is under $20.



ARLISS Extreme Mission

[20] An ARLISS ComeBack Competition mission independently deploys a satellite just after airframe apogee. Each satellite then deploys the recovery method of choice. Parachute then wheels. Quadcopter. Wings. Parawing. Anything. The project that gets closest to the present GPS coordinates on the Black Rock playa - wins. The most recent winner in 2019, a young woman led team from Japan used a deep learning vision system plus GPS to literally hit the target 2 times in 3 flights - with the third attempt less than a centimeter away.

ARLISS Extreme, while still under development, has been designed to carry 3x 1p S4 payloads as captive payload halfway to the Karman line. Its foundation architecture is the successful Carmack Prize winning flight above 100k' in 2012.



Documentation

S4 is documented at GitHub[21]. Current software, documentation and the 3D printer package.

S4 is open source and freely available to be used by anyone - though attribution is a wonderful thing.   We ask that users share missions, new sensors and modifications with the entire S4 community.

Contact Ken Biba at kenbiba at icloud.com for more information.

Future Work

Technology changes rapidly, as we are at a wonderful time of innovation. Modern microcomputers, wireless communications, sensors and 3D printing encourage a rapid fail fast development methodology.   Updates to the current system are in progress.

- Updated communications to include S4 to S4 communications to enable satellite swarms using LoRa and WiFi.   Additional beacon modes as backup in challenging environments like LEO.
- New sensors as they are available.
- New processors and storage.
- Distributed ground stations increasing coverage sharing telemetry via Internet dashboards.

[21] https://github.com/kenbiba/S4