2017 S4: Small Satellites for Secondary Students
Technology and Program Overview

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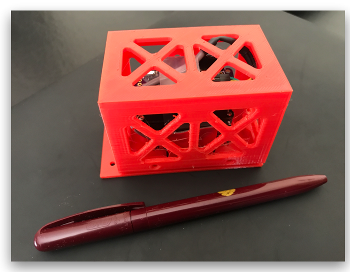
The S4 (Small Satellites for Secondary Students) student satellite system is an opportunity to do payload science targeted to advanced middle and high school students - but also useful to a much wider range of curious experimenters. It is based on the over 17 year ARLISS[1] program of university student payloads that produced CanSats and autonomous recovery robots.

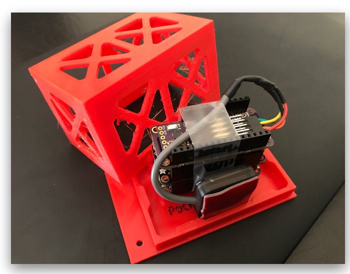
The S4 vision is to imagine a progression of science missions rooted in missions on the ground or on small rockets such as TARC[2], progressing to missions to a few thousand meters on High Power hobby rockets (like ARLISS), extending to PocketQube sounding rocket or high altitude balloon missions to 10s of kilometers high (like ARLISS Extreme) and eventually to PocketQube missions deployed into Low Earth Orbit. Each step stretching student abilities with incremental increase in scope, risk and cost.

The wide range of sensors and extensibility of the S4 system allow for missions in the atmosphere or the ground that are largely only limited by the user's imagination.

- Atmosphere science measuring dust, organic compounds, temperature, pressure, humidity, gases
- Measurement of ground and vegetation using visible and IR imaging
- Vehicle dynamics measuring drag, vehicle orientation, position, trajectory using GPS, accelerometers, gyros, magnetometers
- Airframe control for recovery thru servos and/or pyrotechnics
- Satellite recovery after apogee deployment[3] via parachute or mechanically actuated recovery like steered parasails
- Gamma ray radiation measurements.



Each S4 satellite payload is inspired by the new standard 1.5p PocketQube[4] picosatellite format (5 x 5 x 7.5 cm, ~300 gm) - invented by Professor Bob Twiggs, inventor of CanSats and co-inventor of CubeSats. Each S4 satellite contains an array of sensors and is programmed as an advanced Internet of Things computer. Configurations with minimal sensors can be as inexpensive as $50, and full-up configurations with multiple sensors and telemetry can reach over $200. Core data collection loops can exceed 100 Hz, with full sensor complement loops can deliver 30 Hz of multi sensor data collection performance.



[1] A Rocket Launch for International Student Satellites is an international high school and university competition for autonomous robotic student satellites held for the last 17 years by the AeroPac rocketry club at Black Rock Nevada. www.arliss.org

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

[3] Standard ARLISS CanSat deployment.

[4] 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 are the successor - reducing the key dimension from 10 cm to 5 cm - recognizing the increase in electronics capability at small size. A number are now in orbit with more on the way. https://en.wikipedia.org/wiki/PocketQube

For all but the most basic platforms, S4 uses modern spread spectrum long range radio communications to communicate to ground stations and download telemetry from the mission.

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 or programming.

S4 satellites are designed to be flown on rockets as small as TARC rockets or drones that fly a standard hen's egg size payload on F and G motors to 1000' up to High Power sounding rockets or balloons that reach the top of the stratosphere[5]. S4 satellites can be configured for either captive flights or to be deployed at apogee on a recovery device for independent descent. The PocketQube format allows for an incremental transition to an ultimate space capable packaging suitable for LEO deployment.

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.

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 telemetry of sensor data to the ground and for receipt of commands to the satellite;
- Data collection that
  - polls configured sensors,
  - periodically saves sensor data to local storage - generally a microSD flash memory card,
  - wirelessly transmits sensor data to the ground station,
  - listens for commands from the ground station to the satellite.
- Ground station software to receive telemetry from mission satellites and transmit commands from the ground.

For S4Egg and S4 Arduino this package is written in C/C++ and is hosted on the Arduino IDE. A version in Python is in development for the S4Pi.

Platforms

2017 S4 provides three standard platforms to accommodate different missions. All platforms are powered by a 3.7V LiPo battery sized for the mission and configuration. Small configurations, such as S4Egg are powered by as little as 100 mAh, while more robust configurations require 500 mA, each delivering hours of operation.

There are three S4 baseline configurations.

[5] Like the ARLISS Extreme sounding rocket, that can carry two S4Arduino payloads over 100k' AGL on commercial motors totaling less than 30k Nsec of total impulse.

Platform	Package	Processor	Data Storage	Communications	Sensor Capacity	Scope
S4Egg	3D printed plastic package in hen's egg size, to match TARC payload	Arduino Zero C/C++	microSD	None	< 4	Entry level S4 satellite designed to be flown in TARC compatible rockets as a subset of PocketQube
S4Arduino	1.5p PocketQube, 3D printed plastic	Arduino Zero C/C++	microSD	LoRa telemetry WiFi (optional)	< 10	Standard Arduino platform with local storage, telemetry and substantial sensor capacity.
S4Pi	1.5p PocketQube	Raspberry Pi Zero W Python	microSD	LoRa + WiFi - 802.11n telemetry	< 10	Standard PQ with RaspPi Pi platform. Additional computing capability, high performance telemetry,

S4Egg is based on Adafruit Feather M0[6] platform. It provides an Arduino compatible 48 MHz ARM processor with substantial processing, memory, and I/O resources[7]. The S4Egg has a standard baseline sensor suite designed for crowd sourced earth science of atmospheric temperature, humidity, pressure, CO^2 concentration and Total Volatile Organic Compound (TVOC) measurement. It has a limited capability for sensor expansion using standard S4 sensor interfaces. It has no baseline telemetry capability and stores mission data locally on microSD. The platform includes a serial port, a digital/analog port and an I2C port for sensor expansion.

S4Egg is programmed in the C/C++ Arduino environment using the Arduino IDE development environment. The standard S4 mission program can be used to collect data and as a baseline for adding new sensors and experiments.

Processor, memory, I/O, microSD storage	https://www.adafruit.com/product/2796	$19.95
S4 sensor board	To be published	~$3.00
3x4 sensor interface header	https://www.adafruit.com/product/816	$0.74
Humidity, temperature, atmospheric pressure, equivalent CO2, Total Volative Organic Compounds sensor	https://www.tindie.com/products/onehorse/air-quality-sensors/	$35.95
Feather low profile female header	https://www.adafruit.com/product/2940	$1.50
Feather short male header	https://www.adafruit.com/product/3002	$0.50
150 mAh LiPo battery	https://www.adafruit.com/product/2750	$6.95
3D printed plastic egg enclosure	To be published	~$3.00

[6] https://www.adafruit.com/product/3178, 48 MHz ARM Cortex M0, 256k FLASH, 32k RAM memory. The Adafruit Feather family includes multiple integrated radio of options including LoRa, WiFi and conventional narrow band FSK.

[7] The Feather M0 is about five times "bigger and faster" than the classic Arduino.

The S4Arduino is based on the same basic hardware platform as the S4Egg - the Adafruit Feather M0. It adds the baseline S4Arduino sensors include: flight capable GPS, 3x accelerometer, 3x gyro, 3x magnetometer, external temperature, atmospheric pressure, battery status. Possible optional sensors include CO^2 concentration, humidity, UV+IR+visible light intensity, simple IR imaging, gamma ray radiation, dust and external video. A microSD card provides for local recording of sensor data and a LoRa wireless data connection provides for real-time data 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.

Processor, memory, I/O, microSD storage	https://www.adafruit.com/product/2796	$19.95
LoRa telemetry radio, Feather	https://www.adafruit.com/product/3231	$19.95
S4 sensor board	To be published	~$3
Atmospheric pressure (to over 100k' MSL), temperature, 9DOF orientation	https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	$29.95
3x4 sensor interface header	https://www.adafruit.com/product/816	$0.74
uBlox 3D dynamics flight rated GPS		$20.00
Feather low profile female header	https://www.adafruit.com/product/2940	$1.50
Feather short male header	https://www.adafruit.com/product/3002	$0.50
Feather stacking header	https://www.adafruit.com/product/2830	$1.25
3D printed 1.5p PocketQube enclosure	To be published	~$3

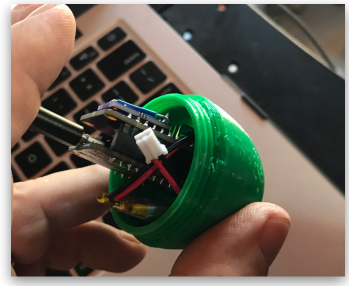
S4Pi is based on the Raspberry Pi Zero W platform. The platform includes both a LoRa radio, a WiFi radio, a microSD for local storage, flight capable GPS, 3x accelerometer, 3x gyro, 3x magnetometer, temperature, pressure and battery status. A standard RaspPi video camera is included. Possible optional sensors include

Raspberry Pi Zero W	https://www.adafruit.com/product/3400	$10.00
S4Pi Motherboard	To be published. Processor board + 3 extensions pHats	~$3
S4Pi Sensor Board	To be published. Extension pHats hosting 9DOF sensor and LoRa telemetry radio	~$3
S4Pi Camera	https://www.adafruit.com/product/3099	$29.95
S4Pi Camera Cable	https://www.adafruit.com/product/3157	$5.95
900 MHz LoRa Daughterboard	https://www.adafruit.com/product/3072	$19.95
MS5611+LSM9DS1	https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/	$29.95
1.5P package	To be published.	~$3

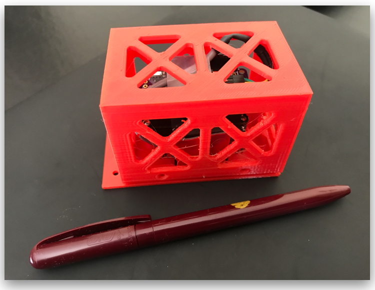
CO2 concentration, humidity, UV+IR+visible light intensity, simple IR imaging, gamma ray radiation, and dust. The platform includes a serial port, a digital/analog port and an I2C port for sensor expansion.

Packages

S4 has two packages for the three platforms.



The S4Egg package is a 3D printed plastic enclosure, in the volume of a chicken egg - 45mm in diameter. It has sufficient capacity for the core Arduino processor, battery, the baseline S4Egg sensors and extension connectors for I2C, serial, and digital/analog ports.



S4Arduino and S4Pi share the 1.5p PocketQube package. It is a 3D printed 5x5x7.5 cm plastic enclosure designed to hold the core processor, baseline sensors, battery, antennas, and additional sensors. About half the volume of the S4Arduino is available for optional sensors.

The S4 electronics are expected to space capable for short missions to LEO. It is anticipated that the plastic PocketQube form factor will be upgraded to a 3D printed space cable material and format.

Standard Sensor Interface

S4 defines three external sensor interfaces, each defined a simple four wire interface using a standard .1" 4 pin connector. All platforms use the same interfaces. Standard Arduino C/C++ sensor libraries are shared between S4Egg and S4Arduino in the S4 Mission Software. A separate library is necessary for the Python version of SMS for the S4Pi.

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

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

S4Pi also supports USB.

Sensors

The S4 system uses an open ended collection of sensors to measure position, light, atmosphere, radiation and multispectral imaging. The same sensor interfaces are used by all platforms.

The following table represents sensors that can fit in the package, have supported drivers for at least one S4 platform, and are believed to collect useful data during rocket flight.

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

Measurement	Sensor	Description/Link	S4Egg		S4Arduino		S4Pi	
			s	o	s	o	s	o
Time	uBlox 7 GPS Cortex M0 clock	.5 sec with 2 Hz refresh rate.		√	√		√	
Location	uBlox 7 GPS	3m RMS horizontal precision.		√	√		√	
Geometric Altitude	uBlox 7 GPS	10m RMS vertical precision.		√	√		√	
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/		√	√		√	
	Bosch BNO055	3D acceleration sensor. Up to 16gs. Hardware absolute position: roll, pitch, yaw. https://www.adafruit.com/product/2472		√		√		
Magnetic field	ST LSM9DS1	3D magnetic field sensor. Software absolute position: roll, pitch, yaw. https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/		√	√		√	
	Bosch BNO055	3D magnetic field sensor. Hardware absolute position: roll, pitch, yaw. https://www.adafruit.com/product/2472		√		√		
Rotation	ST LSM9DS1	3D gyro, rotation sensor. Software absolute position: roll, pitch, yaw. https://www.tindie.com/products/onehorse/lsm9ds1ms5611-breakout-board/		√	√		√	
	Bosch BNO055	3D gyro, rotation sensor. Hardware absolute position: roll, pitch, yaw. https://www.adafruit.com/product/2472		√		√		
Ambient IR light	AMS-TAOS TSL2591	https://www.adafruit.com/product/1980		√		√		√
Ambient Visible light	AMS-TAOS TSL2591	https://www.adafruit.com/product/1980		√		√		√

Measurement	Sensor	Description/Link	S4Egg		S4Arduino		S4Pi	
			S	O	S	O	S	O
Ambient UV llght	Vishay VEML6070	https://www.adafruit.com/product/2899		√		√		√
Spot IR temperature sensor	Melexis MLX90614	10 degree FoV spot IR sensor. Determine average ground temperature. Vegetation. https://www.sparkfun.com/products/9570		√		√		√
IR imaging sensor	Panasonic AMG 8833	8x8 array of IR sensors for primitive IR imaging. 60 degree total FOV https://www.tindie.com/products/onehorse/grid-eye-8-x-8-ir-array/				√		√
CO^2	AMS CSS811	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/	√			√		√
Dust	Sharp GP2Y1010AU0F	Optical dust sensor http://www.waveshare.com/dust-sensor.htm				√		√
Gamma Radiation	First X100-7	PIN silicon photodiode radiation detector. Detects 0.002-1.0 MeV gamma rays. https://www.sparkfun.com/products/14209				√		√
Local video		S4 local stored video https://www.adafruit.com/product/3202				√	√	
Streaming video		Video, both stored locally and streamed to ground in real-time https://www.adafruit.com/product/3414					√	

Communications and Telemetry

The S4 system defines two wireless communications methods, one for long range, low power telemetry and the other for shorter range, high performance communications.

Platform	Telemetry Choices
S4Egg	None LoRa 868/902-928 MHz (optional)
S4Arduino	LoRa 868/902-928 MHz WiFi (2.4 GHz, 802.11n, 20 dBm (optional)
S4Pi	LoRa 902-928 MHz/868 MHz WiFi (2.4 GHz, 802.11n, 20 dBm

An emerging wireless standard for the Internet of things, LoRa[8], is used as the basis for long range, low power S4 telemetry service in the 868 MHz unlicensed band in Europe and the 902-928 MHz unlicensed band in the Americas. LoRa is based on a variant direct sequence spread spectrum modulation system that provides up to 30 dB of additional radio link budget depending on desired throughput vs range performance. It is packaged for high volume applications with a single chip controller+radio implementation available for less than $5 with 20 dBm of TX power and over 148 dB of potential effective receiver gain.

The radio link can be software configured to trade off range vs throughput. Tracking ranges exceeding 200 km are anticipated[9] at 900 MHz using omnidirectional antennas in both payload and ground station. Modest directional ground station antennas can double that range. Telemetry speeds range from 100s of b/s ranging to 10s of kb/s are possible. S4 uses the standard RadioHead[10] Arduino communications library to provide the basic protocol structure. S4 uses software tunable LoRa radios in the 902-928 MHz unlicensed band.

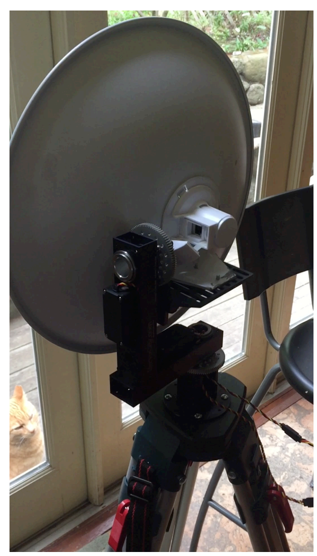
S4's telemetry protocol has bidirectional capability - for telemetry from the satellite and commands from the ground. The protocol is Listen-Before-Talk allowing multiple shared satellites on a common telemetry frequency channel. Satellites on the same channel can share grounds stations and satellite telemetry can be received by multiple ground stations. Up to 255 satellites and ground stations can be configured on the same frequency channel.

WiFi is used for high speed, mulit-megabit communications using UDP/TCP. Early S4 prototypes using WiFi communications demonstrated rocket telemetry performance up to 3km AGL. With a high gain, inexpensive ground station antenna WiFi ranges exceeding 20 km to S4 payloads look to be possible. Both S4Arduino and S4Pi can be configured with a WiFi link. The LoRa telemetry is used for positioning telemetry to the ground station, the payload positioning telemetry is used to point the ground station high gain WiFI antenna. S4 currently uses 802.11n WiFi radios in the 2.4 GHz unlicensed band.

Telemetry Ground Stations

S4Arduino and S4Pi have telemetry ground stations that attach to laptops via USB to store and collect telemetry.

The basic LoRa ground station is a single board Adafruit Feather M0 with a LoRa radio with an omnidirectional antenna. The ground station connects to a USB port on a local laptop for a .csv telemetry data stream.



An enhanced ground station adds WiFi for sharing telemetry with Internet hosts via local WiFi hotspot communications to Internet gateways[11]. The S4 Mission Software includes the capability of Internet dashboards monitoring selected mission data on common Internet of Things Internet services.

The advanced S4 ground station adds local GPS, 9DOF positioning sensor, and servo control to enable the ground station to take position telemetry from the payload using LoRa and to then determine the tracking vector to the satellite from the ground station. The ground station then uses this tracking vector to control the servos on the antenna tracking mount to point the WiFi antenna at the payload.

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

[9] European high altitude balloon experiments at lower transmitter power and at 433 MHz validate this assumption.

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

[11] Such as those supported in most modern smartphones.

The WiFi antenna has a builtin 802.11n dual polarized MIMO access point[12] delivering Ethernet TCP/UDP packets from the payload. This capability allows for high performance telemetry of streaming video and IR imaging.

The Adafruit Feather platform also provides the ability to add displays and other sensors for differential measurement between satellite and ground station.

How To Participate

S4 is open source[13] and freely available to be used by anyone. We ask that users share missions, new sensors and modifications with the S4 team in order to share that with the entire S4 community.

The National Association of Rocketry is sponsoring two early programs in 2017 to kickstart S4 in student rocket science. NAR is funding S4 satellites for TARC Finalists - but any student team can join and participate.

The **Student Crowdsourced Atmosphere Pollution** Study[14] - SCAP - uses S4Egg, on the ground and in mid-power rockets to collect measure humidity, temperature, pressure, CO^2 and Total Volatile Organic Compounds in the atmosphere column. Data taken by each team will be aggregated and shared with all teams collecting data allowing analysis not just of each team's data, but all the SCAP measurements. NAR has sponsored 30 S4Eggs for 2017 TARC Finalists but anyone can join in.

ARLISS **Explore the Earth** - encourages students to design, implement and report a science experiment about rocketry, the Earth or its atmosphere using the S4Arduino on high power rocket[15]. NAR is sponsoring six TARC teams to do science experiments with S4Arduino but anyone can participate. Teams request participation by a science mission experiment proposal, which they then design and fly with a local HPR flier. They then write up their results as a science experiment and submit back to the S4 project team for evaluation. The top two teams will then be funded for an ARLISS Extreme sounding rocket flight with their satellite to the top of the stratosphere - over 100k' high at Mach 3.

Contact Ken Biba at kenbiba@icloud.com.

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[12] https://www.ubnt.com/airmax/rocketdish-antenna/ These dish antennas are dual polarized MIMO 802.11n with 24 dBm antenna gain, 28 dBm Tx power and -96 dB RX sensitivity at 6 Mb/s link rate. Common consumer prices are under $80.

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

[14] https://github.com/kenbiba/S4/blob/master/2017%20S4Egg4.pdf

[15] https://github.com/kenbiba/S4/blob/master/2017%20S4Arduino5.pdf