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 science experiments as rocket and balloon science 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 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 concept to secondary students. The NASA sponsored Rising Data[7] 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[8], 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[9]) 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.

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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

[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

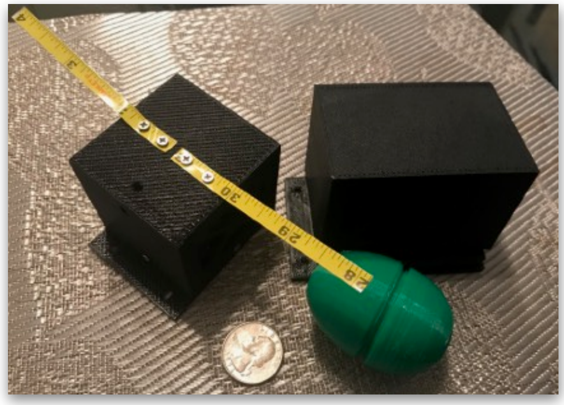
[6] https://www.dropbox.com/s/10g3w2qxc5axnbo/S4%20Student%20Satellite.pdf?dl=0

[7] http://lbym.sonoma.edu/RisingData/user/register

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

[9] 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

- 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[10] via parachute or mechanically actuated recovery like steerable parasails or parawings with autonomous guidance;
- Cosmic gamma ray spectrometer analysis in the exosphere.



Each 2019 S4 satellite payload is inspired by the new standard PocketQube picosatellite format (in the 1p format, 5 cm on a side, in the 1.5p 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 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 $200. Core data collection loops can exceed 20 Hz, with multi sensor collection loops delivering 5-10 Hz.

S4 collects data locally on the satellite in non-volatile flash memory. Higher end 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.

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 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. S4 satellites can be configured for either captive flights[11] or to be deployed at apogee on a recovery device (such as a parachute) 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.

Missions

Science is about 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 three amazing recent innovations in citizen science:

[10] Standard ARLISS CanSat deployment.

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

- Low cost sounding rockets and high altitude balloons,
- Robots and low cost environmental sensors,
- 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 S4Egg at low altitude, and a more complex one like S4Qube to the stratosphere. S4Egg is suited more for younger learners and simpler missions (say middle school) while S4Qube for more sophisticated learners and more complex missions (say advanced high school). These are illustrative not prescriptive.

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

S4Egg has a relatively simple portfolio of atmosphere sensors with data sampled at 10 Hz:

- Mission time to the millisecond,
- temperature,
- humidity (water vapor content),
- air pressure,
- eCO2 and
- volatile organic compounds (TVOC) - CO, alcohols, atmospheric pollutants.

It is configured as a 3D printed PLA enclosure in the shape of a hen's egg replacing the payload of a TARC rocket. It weighs ~30 grams and can be thought of as a sensor measuring the basic chemical content of the Earth's atmosphere column.

S4Qube has a rich portfolio of 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 S4Qube 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.

It is configured as a 3D printed PLA 50mm 1p cube for either captive flight or independent deployment for parachute recovery. It weights about ~150-200 grams. Spread spectrum wireless telemetry allows for independent tracked recovery. Additional sensors can be configured on standard extension busses (I2C, serial, 1-Wire, DIO). Open source data collection and telemetry software is Arduino/C++ based.

S4Qube has an experimental multispectral imaging sensor cluster combining a low resolution false color visible light camera, coaxial with a thermal imaging camera and an optional spectrometer designed for ground examination.   It is hopes that this imaging sensor cluster can be used for false color vegetation and crop analysis[12].

S4Egg Missions

S4Egg 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

S4Qube Missions

A rocket based mission to 30k' can take advantage of the rich portfolio of S4Qube'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 S4Qubes 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

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

How much energy did the 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

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 dashboard downloads mission data from the satellite.

For S4Egg and S4Qube this package is written in C/C++ and is hosted on the standard Arduino IDE.

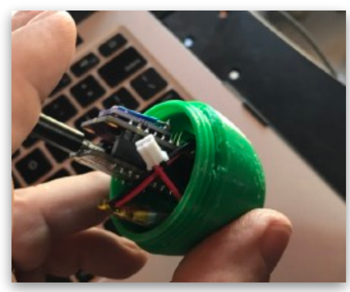
The S4 hardware also support Python for users that prefer to port the mission software to that environment.

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

S4 Platforms

S4 provides two 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 350+ mAh, each delivering hours of operation.

Platform	Package	Processor	Data Storage	Communications	Sensor Capacity	Scope
S4Egg	3D printed plastic package in hen's egg size, to match TARC payload	ARM Cortex M0+ C/C++	2 MB Flash	None	< 4	Entry level S4 satellite designed to be flown in TARC compatible rockets as a subset of PocketQube
S4Qube	1p PocketQube, 3D printed plastic	ARM Cortex M4 C/C++	22 MB Flash	LoRa telemetry	< 10	Standard Arduino platform with local storage, telemetry and substantial sensor capacity.



S4Egg is embedded in a 3D printed plastic enclosure, in the shape and volume of a chicken egg - 45mm in diameter. S4Egg is based on Adafruit ItsyBitsy M0 Express platform.   It provides an Arduino compatible 48 MHz ARM processor with substantial processing, memory, and I/O resources.   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 2 MB of flash. The platform includes a serial port, a digital/analog port and an I2C port for sensor expansion.

	48MHz Cortex M0+ ARM Processor, 256KB program/32KB SRAM memory, I/O, 2MB flash mission storage, LiPo battery management	https://www.adafruit.com/product/2796	$11.95

	S4Egg Sensor board I2C Serial port DIO Environmental	Custom PCB, To be published	~$3.00
	Humidity, temperature, atmospheric pressure, equivalent CO2, Total Volatile Organic Compounds sensor	https://www.tindie.com/products/onehorse/air-quality-sensors/	$35.95
	150 mAh LiPo battery	https://www.adafruit.com/product/2750	$6.95
	3D printed plastic egg enclosure	To be published	~$3.00

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.

The S4Qube is based on an enhanced processor platform - the ARM Cortex M4 - the Adafruit ItsyBitsy M4 Express. It adds the baseline S4Qube 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. Like S4Egg, it is programmed with the Arduino IDE and the standard S4 mission software.

The power of the Cortex M4 adds substantial capabilities to S4 - particularly in the areas of imaging and signal processing with a minimal increase in cost.

S4Qube 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 daughterboard sensors designed for the science mission in mind.

There is room for one or more board of similar 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 particulate matter sensor, the experimental multispectral imaging board or the radiation sensor can be packaged externally - mounted to the aft side of the package.

	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.

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.

S4Qube is a 3D printed 5x5x5 cm plastic enclosure designed to hold the core processor+memory, baseline sensors, battery, antennas, and additional sensors. S4Qube can be flown on standard HPR airframes on G thru O motors as a captive payload or can be deployed for independent recovery under parachute.

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 a 3D printed space capable material and format.

Standard Expansion Interface

S4 defines three external sensor interfaces, each defined a simple four wire interface using SparkFun's QWIIC[13] 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 shared between S4Egg and S4Qube in the S4 Mission Software.

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 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 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 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.

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

Measurement	Sensor	Description/Link	S4Egg		S4Qube	
			s	o	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	S4Egg		S4Qube	
			s	o	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				√

Communications and Telemetry

An emerging wireless standard for the Internet of things, LoRa[14], is used as the S4 basis for inexpensive, long range, low power S4 telemetry service in 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.

The LoRa radio link can be uniquely software configured to trade off range vs throughput. Low data rate ranges to LEO have 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[15] Arduino communications library to provide the basic protocol structure. S4 uses software tunable LoRa radios in the 902-928 MHz unlicensed band.

The basic S4 ground station is an S4Qube 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.

Documentation

14 https://www.lora-alliance.org/What-Is-LoRa/Technology

15 http://www.airspayce.com/mikem/arduino/RadioHead/

S4 is documented at Hackaday[16] 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.

[16] https://hackaday.io/project/22134-student-science-satellites-and-sounding-rockets