The AMSAT-UK FUNcube Handbook

First Edition

Amsat-UK

The FUNcube Handbook

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FUNcube Flight model (left) and Engineering model

The FUNcube project is being undertaken by a team of (less than 10) experienced volunteers drawn from radio amateur members of AMSAT-UK, AMSAT-NL and others and is part funded by the Radio Communications Foundation - a Registered Charity.
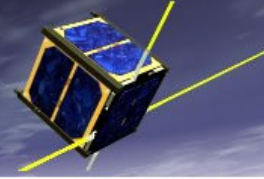
While this handbook refers mainly to FUNcube-1, readers should note that similar hardware and software was provided to the UKube-1 spacecraft (sponsored by the UK Space Agency) as a sub-system which will provide almost the same functionality.

Contents

Cover graphics: FUNcube-1 flight model

What is a CubeSat
(with acknowledgments to Wikipedia)

A CubeSat is a type of miniaturized satellite that usually has a volume of exactly one litre (10 cm cube), has a mass of no more than 1.33 kilograms, and typically uses commercial-off-the-shelf (COTS) electronic components.

The majority of development comes from academia, but several commercial companies have built CubeSats. The CubeSat format is also popular with amateur radio satellite builders. The price tag, far lower than most satellite projects, has made CubeSat a viable option for schools and universities across the world.

The CubeSat specification accomplishes several high-level goals. Simplification of the satellite's infrastructure makes it possible to design and produce a workable satellite at low cost. Encapsulation of the launcher-payload interface takes away the prohibitive amount of managerial work that would previously be required for mating a piggyback satellite with its launcher. Unification among payloads and launchers enables quick exchanges of payloads and use of launch opportunities on short notice.

The standard 10×10×10 cm basic CubeSat is often called a "1U" CubeSat meaning one unit. CubeSats are scalable along only one axis, by 1U increments. CubeSats such as a "2U" CubeSat (20×10×10 cm) and a "3U" CubeSat (30×10×10 cm) have been both built and launched; current maximum capability is 6U. Since CubeSats are all 10x10 cm (regardless of length) they can all be launched and deployed using a common deployment system usually called a POD (Picosatellite Orbital Deployer).

Project History and Overview

AMSAT-UK launched its new satellite project, called FUNcube, in October 2009. The project received major initial funding from the UK's Radio Communications Foundation (RCF) charity. The RCF were able to provide this funding following a legacy (enough to pay for the launch) from G7HIA which specified that it should be used for a 'space' project. RCF and Gift Aid have helped in other ways too.

The project is not just from AMSAT-UK because AMSAT-UK are unable to get a licence for the flight from the UK's Space Agency under the UK's Outer Space Act (for reasons mostly of cost). So the satellite flying will be registered as Dutch at the ITU. Because of this AMSAT-UK entered into a joint venture with AMSAT-NL who produced the RF board, the ASIB board and, most importantly, signed the launch contract.

The FUNcube project is to create an educational CubeSat which is intended to enthuse, excite and educate students about radio, space, physics and electronics. It will also support educational Science, Technology, Engineering, and Maths (STEM) initiatives.

Teachers should visit the www.esa.int/Education/Teachers_Corner website

FUNcube-1 will fly as a stand-alone 1U CubeSat and FUNcube-2 will be part of the UKube-1 3U spacecraft. The satellite design uses as many off-the-shelf subsystems as possible to reduce complexity and development time, and to keep the financial risk of the mission to a minimum. The primary mission is to provide downlink telemetry that can be easily received by schools and colleges for educational outreach purposes. When not in educational mode the spacecraft switches on a transponder for use by radio amateurs.

The target audience is largely students at both primary and secondary levels and the project includes the development of a simple and cheap ground station facility operating on VHF frequencies in the Amateur Satellite Service.

This ground station is simply a USB unit, we call it a dongle, which will receive signals direct from the satellite and transfer the data to specially developed graphical software running on any Windows computer. The required antenna should be no more than a basic VHF monopole or dipole.

USB Dongle

The telemetry will provide information about:
- On board temperatures – internal and external
- Voltages and currents flowing from the solar arrays and to/from the battery
- Other onboard data
- Temperatures from external metal strips which have different finishes to provide an enhanced demonstration of the "Leslie's Cube" experiment (one of the traditional school demonstrations of how objects emit heat)

Additional educational objectives and opportunities offered by the project include:
- "Whole Orbit Data" for orbit illumination and eclipse demonstrations
- More advanced demonstrations relating to antenna radiation patterns and levels of solar radiation. Long term study of the effects of radiation on microcircuits and other subjects would also be possible
- Integration into the maths and physics curricula at primary and secondary levels
- Demonstrations of radio communications at schools
- Display of an actual FUNcube "demo-sat" in the school
- Involvement of university undergraduates for advanced studies
- Greetings messages (like a tweet from space)

The FUNcube project also includes the development of suitable software (the Dashboard) to enable the display of the telemetry data. This software has been developed in collaboration with teachers and will be available in different "flavours" to accommodate a variety of age groups. It will also be capable of visually showing the spacecraft attitude and spin rates etc.

In addition to displaying the telemetry, the computer could also show a live "tracking map" display with predictions for the particular school location (NB a separate program is required to do this).
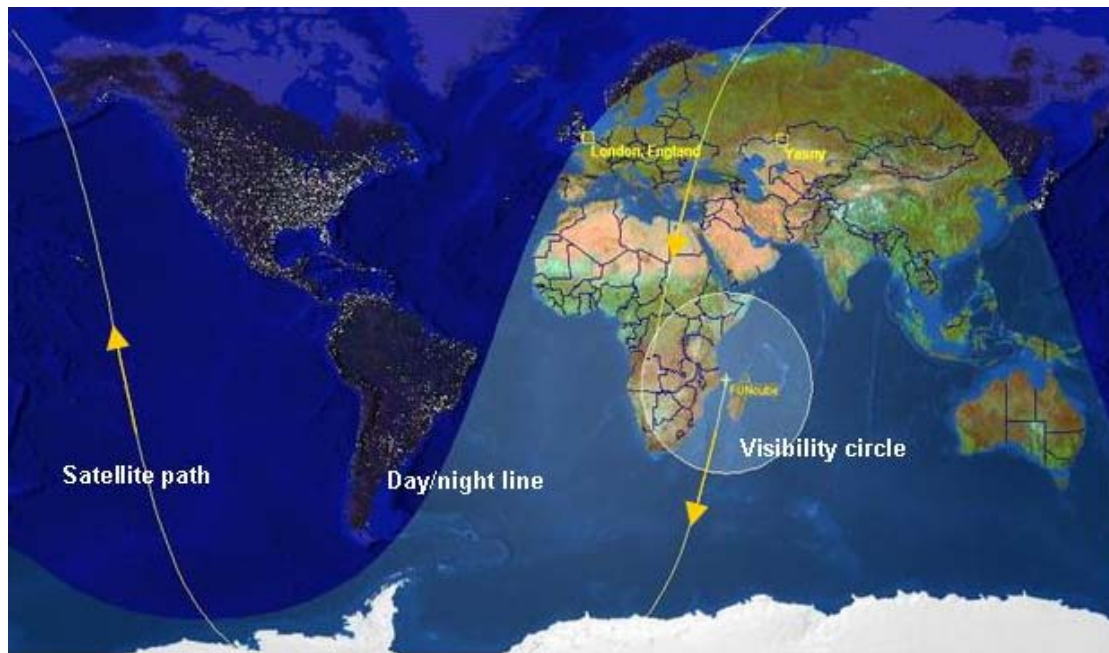
Tracking map

Also the payload will allow the uploading (indirectly via a moderated host) of short greetings messages for schools to use, and the transfer of the data received by a ground station onto a central database. This central data will also be available to be retrieved by anyone else for display and analysis.

It is possible that inter-school competitions for, say, the most data collected in a period, the most inventive use of the data, or reports of "lessons learnt" from different age groups could be easily established with prizes and presentations.

Measuring just 10x10x10 cm, and with a mass of less than 1kg, modern components have allowed the design of a very sophisticated spacecraft. FUNcube-1 is the first CubeSat designed to benefit younger age groups and will be the first UK CubeSat to reach space. It is anticipated that both FUNcube-1 and FUNcube-2 (on UKube-1) will be launched into Sun Synchronous Low Earth Orbits at an altitude of roughly 600-800km using one of a number of launch opportunities that exist for CubeSat missions.

In such an orbit, the satellite passes over countries every day usually three times in the morning and three times in the evening (local time). Outside of school times and at weekends FUNcube will be made available to radio amateurs to use for their communication experiments.

Spacecraft Systems
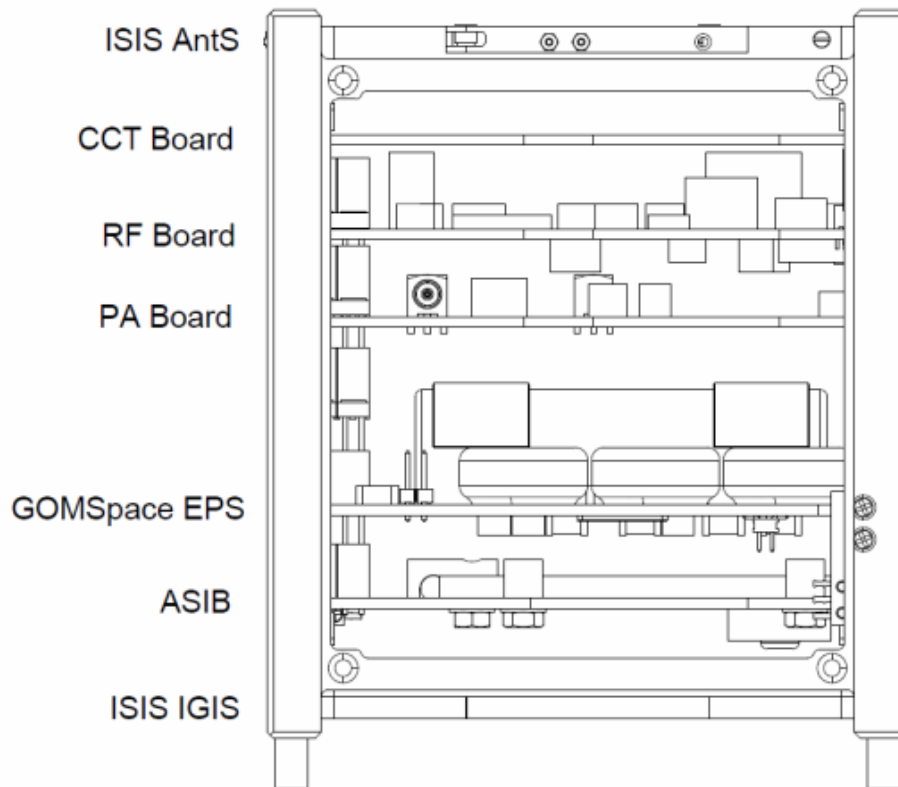
Antenna System AntS (ISIS)

FUNcube-1 has one dipole on 145 MHz and another dipole on 435 MHz, both supplied by ISIS. The actual antenna elements are made from material similar to that used in roll-up metal tape measures, such that, when released, they will spring out automatically. Antennas are deployed by melting a wire which is routed over a set of redundant resistors which can be heated on command. When the wire melts it releases the lid allowing the antenna to deploy. The antennas will be deployed (one element at a time) approximately 10 minutes after ejection from the ISIPOD; this is to make sure that we are at a sufficient distance from the other payloads so we don't hit anything.
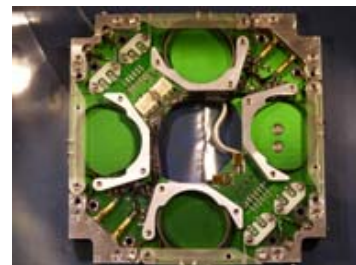
RF Board (AMSAT)

The RF board performs the following functions:
- Reception of a single FM channel in the 435MHz amateur satellite band and demodulation to an audio signal which is presented to the CCT board for command decoding

- Modulation of BPSK telemetry. The board takes audio from the CCT board, modulates it, up-converts the signal to a frequency in the 145MHz band, and finally boosts the signal for final amplification by the PA board
- Receiver and AGC for the inverting linear transponder, this converts a 20kHz bandwidth from 435MHz to 145MHz

PA Board (2m Amplifier) (AMSAT)

The power amplifier board increases the power level of the beacon and transponder signals.
The signals, at 145MHz, arrive from the RF board with a maximum power of 30mW or +15dBm. These low level signals are amplified to 400mW (+26dBm) before being sent to the transmit antenna. The RF amplifier is a single stage class AB amplifier using a Mitsubishi RD02MUS1 power MOSFET. The amplifier uses the unregulated battery voltage which, in normal use, will vary from 6.8 to 8.2 Volts. The amplifier is followed by a low pass filter which removes frequencies above 160MHz. The filter includes traps that add additional attenuation to the third harmonic, which is close to the command and transponder UHF input frequencies.

In addition to the RF amplifier, the PA board contains four sensors that gather data for the satellite's telemetry. The sensors are:
- Supply current to the PA transistor (mA)
- Temperature of the power amplifier transistor (degrees C)
- Forward RF power (mW)
- Reverse (or reflected) RF power (mW)

The temperature of the PA will change during illuminated portions of the orbit, when its temperature will increase due to energy from the sun. Conversely, during eclipse, the temperature will decrease as heat energy flows firstly by conduction to the outer surfaces of the spacecraft and then radiation into space. PA transistor temperature also changes with the amount of use of the communications transponder. Over oceans and polar regions usage of this will be low, while over areas of high population density the transponder will be more heavily utilised causing an increase in temperature.

EPS Power System (GOMSpace - Denmark)

This off-the-shelf unit uses a microcontroller that provides maximum power-point tracking capability, measures and logs voltages currents and temperatures of the system, enables user control etc. The battery uses lithium-ion technology; the two cell battery capacity is 2600mAh at a nominal 7.6Volts
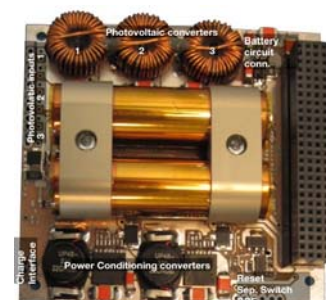
This type of supply is capable of providing power directly from the solar panels in the event that, after some time in space, the battery no longer holds its charge. This will permit sunlight-only operation of the spacecraft after a battery failure; this was an early mission requirement.

Command, Control & Telemetry Board (AMSAT)

The CCT (Command, Control & Telemetry) Board is one of the circuit boards designed and made by members of the AMSAT FUNcube development team. Its function is to control what the satellite does in real-time, for example:
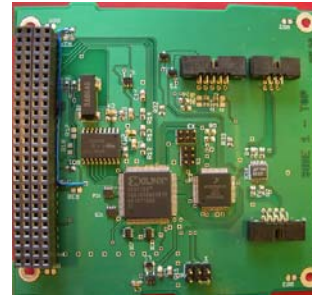
- Automatically switch the satellite from "education mode" to "amateur mode".
- Gather readings from more than 30 sensors on the satellite, e.g. temperatures, battery voltages, currents etc, and convert them into telemetry ready for downlinking via the beacon transmitter.
- Collect and store the data from the Material Science Experiment for a whole orbit to demonstrate variations in thermal performance of materials having different surface finishes, when in a vacuum, as they move from low to high temperature surroundings e.g. from eclipse (very cold) to sunlight (very hot) and vice versa.
- Monitor the main battery voltage, and switch the satellite into a low power mode if the battery voltage drops below a certain preset level.
- Process the telemetry and apply Forward Error Correction (FEC) so that stations receiving the telemetry can do so without errors.
- Communicate with the rest of the satellite via a system known as an I2C bus.
- The board also contains a connector to attach the antenna system, allowing deployment commands to be sent.
- The board has been designed to be very low power (average power consumption 15mW, and peak power 33mW), when not needed the microprocessor can switch itself to a power saving mode.

AMSAT Special Interface Board (AMSAT and ISIS)

This does the passive attitude control, interfacing, and some extra current and voltage measurements.

There is a magnetic attitude stabilization system consisting of two hysteresis rods (on the upper image) and one permanent magnet (the white circular object on the lower image). The hysteresis rods magnetically damp the angular rates in two axes, and the permanent magnet aligns the other axis of the satellite along the direction of the Earth's magnetic field.

Interfacing is performed for: five sun-sensors (not X- facet); four solar panel temperature sensors (not Z +/- facets); two bus voltage sensors; and 3.3v bus current.
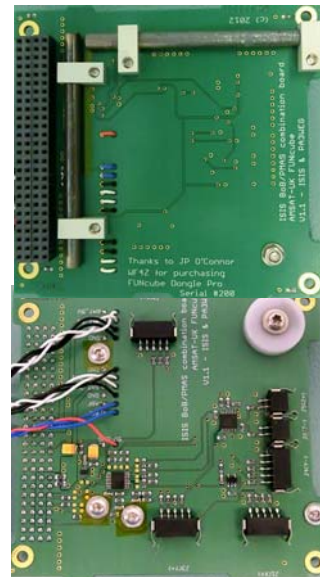
Solar Panels (AMSAT)

The panels come with sun and temperature sensors; they use GaAs Triple-junction technology and have special cover glass for enhanced radiation resistance. Each panel delivers 2.3 watts at three volts (efficiency 28%). Although the efficiency of these panels will deteriorate with time, they are expected to operate at good efficiency for several years at an operating temperature between -40°C and +125°C.

IGIS Board (ISIS)

This is the bottom board and is a standard product from ISIS. It provides a connector for battery charging before flight and enables the vital "ABF" (Add Before Flight) plug to be inserted at the launch site. Without this plug the satellite will not work.

Modes of Operation

- Receive only - all transmitters off, listen for commands from the ground, as required by ITU (International Telecommunications Union)
- Safe mode - low power telemetry beacon only
- Educational mode - high power beacon only. Planned for operation when in sunlight
- Amateur radio mode, low power beacon plus full power transponder. Planned for operation in darkness

Launch & Early Operations

FUNcube-1 should be launched from Russia in late November 2013 into a 600 km sun-synchronous orbit. The required aerial, FUNcube dongle, software and support information is expected to be made available to schools at a low cost shortly thereafter. In the early days of flight the spacecraft will be commanded from the Radio Society of Great Britain's National Radio Centre at Bletchley Park north of London.

Target keplerian elements for launch:

Satellite: FUNcube-1 (AO-73)
Catalog number: 00000
Epoch time: 13325.30750000
Element set: 1
Inclination: 97.5000 deg
RA of node: 40.0000 deg
Eccentricity: 0.0060000
Arg of perigee: 224.0000 deg
Mean anomaly: 288.4304 deg
Mean motion: 14.75200000 rev/day
Decay rate: -3.36e-06 rev/day^2
Epoch rev: 1

Dnepr Launch from
Yasny, Russia, Q4 2013

Payload Operations

During local night (when the spacecraft is in eclipse) the system switches into amateur radio mode: it receives on UHF (435.150 – 435.130 MHz) and transmits on VHF (145.950 – 145.970 MHz plus low power telemetry). In sunlight the spacecraft will be in educational mode, transmitting full power telemetry on 145.935 MHz 1200 bps BPSK. Mode switching timing can be changed by ground command. The satellite has a system to detect when it is in darkness (eclipsed by the earth), and then switches autonomously from Education mode (high power telemetry only) to Amateur Radio mode (low power telemetry plus full power amateur radio transponder).

The amateur radio transponder (part of the RF board) can be used to demonstrate radio communications to schoolchildren and students of all ages. Students should be able to hear amateur radio signals when the satellite passes overhead.

The Amateur Radio Transponder (AMSAT)

Mode UV Inverting transponder
- Power output 300mW PEP, includes 30mW telemetry on 145.935MHz
- AGC range 43dB
- Educational mode : BPSK telemetry at 300mW
- Amateur mode :   30mW BPSK telemetry plus full power transponder
- Satellite can auto switch from "educational" in sunlight to "amateur" in eclipse

Transponder uplink   435.150 to 435.130 MHz
Transponder downlink   145.950 to 145.970 MHz
Telemetry beacon   145.935 MHz

All frequencies have been co-ordinated with IARU (International Amateur Radio Union).

Telemetry

- 1200 bps BPSK with forward error correction, 54 channels
- Telemetry sent in 24 x 5 second frames over a 2 minute period
- Whole orbit data sampled every 60 seconds and stored for 104 minutes
- 'Fast' data sampled at 1 second intervals for 60 seconds
- 9 x 200 character greetings messages; 27 messages stored in memory
- 4.3 seconds of data plus 0.7 seconds of unmodulated BPSK tone
  (A very distinctive sound to enable easy identification by ear.)

Most sensors generate a voltage that is representative of the current, temperature or power being measured. This voltage is converted from analogue to digital form in analogue to digital converters.

All telemetry calibration equations are on the FUNcube website http://funcube.org.uk
The spacecraft also transmits a 24 bit sequence number and a 2 bit satellite identifier

which allows ground station software to identify the satellite and route the telemetry to a 'data warehouse'.

Educational Outreach

The purpose of the FUNcube project is to provide a signal *directly* from a satellite in space that can be easily received by schools and colleges. The target audience is mainly students at both primary and secondary levels. The information will be displayed in an attractive format and provide stimulation and encouragement for students to become interested in all STEM (Science Technology Engineering & Maths) subjects in a unique way.

As well as building the actual satellite, the team has developed a simple and cheap "ground station". This simply requires a small aerial, preferably outdoors, which connects to a special FUNcube USB dongle. This will receive the signals directly from the satellite and transfer the data to specially developed graphical software (the Dashboard) running on any Windows computer.

At primary level we will be able to demonstrate:
- Solar radiation – the power of the sun
- Concepts of planets, orbits, forces and eclipses
- Batteries working in darkness
- Sizes – The International Space Station is large (five double-decker buses) – FUNcube is very small (10cm cube)
- Geography – nations, places, weather etc

At secondary level we envisage being able to demonstrate:
- On board temperatures – internal and external
- Voltages and currents flowing from the solar arrays and to/from the battery
- Temperatures from external metal strips which have different finishes to provide an enhanced demonstration of the "Leslie's Cube" experiment
- Displaying the spin rate by plotting a graph of solar panel current/voltages
- The effect of the magnet on board to align with the earth's magnetic field

Additional educational objectives and opportunities offered by the project include:
- "Whole Orbit Data" for orbit illumination/eclipse demonstrations
- Integration into the maths and physics curricula at primary and secondary levels
- Demonstrations of radio communications at schools
- More advanced demonstrations relating to antenna radiation patterns and levels of solar radiation. Long term effects of radiation on microcircuits and other subjects could also be possible

Additionally the satellite will also enable the uploading (indirectly via a moderated host) of short greetings messages for schools to use and the depositing of the data received on a central database. This central data will then also be available to be retrieved by anyone else for display and analysis.

Materials Science Experiment (MSE)

This examines how heat energy is radiated into space from materials with different surface finishes. In the school science lab we learn that heat energy transfers from a hot material to a cold material by conduction convection or radiation. While conduction in solids and convection in gasses or liquids can be easily demonstrated, the classic Leslie's cube demonstration to show energy transfer by radiation can be unconvincing, as conduction and convection occur at the same time.


Leslie's Cube

Funcube-1 has two aluminium bars mounted on the external surface of the solar panels. One sample is anodized matt black, the other has a highly polished Chrome finish. Both 70 x 4 x 3mm samples are thermally isolated and include thermistors to measure their temperature. As the satellite passes through the illuminated part of its orbit, energy from the sun is absorbed into both metal samples causing an increase in temperature.

The difference in temperature rise between the two samples is not easily predicted as it depends not only on the known attributes of mass, surface finish, specific heat capacity and surface area but also on several unknown variables - for example satellite rotational rate, attitude and the angle of the sample to the Sun. However, when the satellite passes from sunlight into eclipse, energy is lost from both samples by radiation.

The temperatures are sampled once every 60 seconds and stored in the satellites memory. As FUNcube passes over a ground station, data for the last 104 minutes is transmitted via the telemetry. As the time taken for one orbit is approximately 94 minutes, the data will include the last pass through eclipse. The data can be plotted as a graph using the 'dashboard' software. It shows how energy is absorbed and emitted from the samples by radiation at different rates.

In addition to the MSE samples on the solar panels, the aluminium vertical corner struts of the satellite have been produced with one side having a natural silver finish (covered with a blue kapton coating before launch) while the others are matt black. All of these surfaces can be seen on the cover photograph, the formal samples are mounted above the right-hand solar panel. Temperature sensors have also been included and although the structure is screwed together allowing the conduction of heat energy from the corner struts, there should be a measurable difference in the rate of temperature change between them all.

Graphical User Interface – the Dashboard
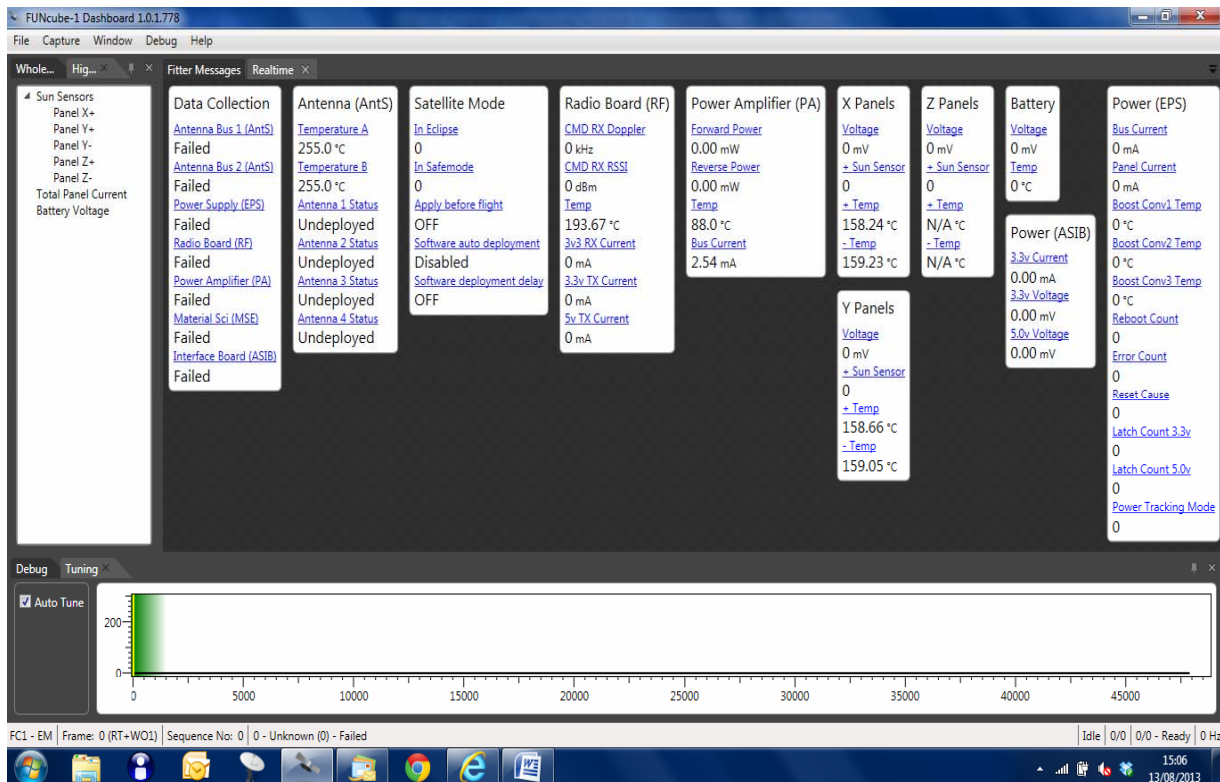
Dashboard front panel

The Graphical User Interface (GUI) is the software which will be available free to anyone interested (both schools and individuals). It will run on a Windows computer, and allow the user to do things like displaying the telemetry. It accepts audio from the FUNcube dongle or from an SSB radio fed into the computer soundcard while it is receiving live signals from the satellite and, if so configured, relay any received telemetry to the Data Warehouse via the Internet (https://warehouse.funcube.org.uk/). In this way we can build up a store of telemetry from all over the world; this data will be available for anyone to analyse. The Dashboard can also display previously recorded data from audio .wav files, IQ wav files or from FUNcubebin recordings.

AMSAT will be making the core software generally available under a Creative Common licence before launch so potential collaborators are encouraged to contact them for more information. A similar, but slightly different, version of this Dashboard is being developed to provide the same functionality for the FUNcube-2 (FC2) sub-system on the UKube-1 spacecraft. The Dashboard has been tested on a variety of different "Windows" machines, from XP through to Windows 8. Software development continues.

At the time of writing (October 2013) the software for linux and Mac OS systems is not yet ready but there are a number of projects in progress to provide decoders for these platforms.

Fitter Messages

What is a Fitter message? 'Fitter' is derived from 'Twitter'. So it's like a tweet, but via FUNcube.

The message is a short (200 characters maximum) text-like message which can be uploaded to the satellite (by authorised ground stations), and which can be transmitted several times every five minutes or so. It will continue to be retransmitted until such time as it is replaced by a new Fitter Message.

Such a message could be something like:

Greeting to xyz school, which will be exhibiting on xyz Date. We hope you receive this message OK! *(room for a bit more)*

There will be memory space for a total of nine such Messages (total 1800 characters).

The FUNcube Dongle

The FUNcube Dongle is a software radio receiver in a USB unit which will receive signals direct from the satellite and transfer the data to computer software. The antenna connects into the dongle's female SMA connector and the dongle does the rest. In fact the dongle will receive much more than satellite frequencies when interfaced to other software. It is designed and built by AMSAT-UK's expert and sales of the unit have benefited the FUNcube project. Basic coverage is at least 150 KHz to 240MHz and 420MHz to 1.9GHz. It contains over 200 components including hardware front end filters and the facility to power an antenna pre-amplifier via the feedline. At the time of publication the latest version was called the FUNcube Dongle Pro+; a search engine will find relevant web pages easily.

Data Formats

Overview

The basic starting point is to use 1200bps BPSK with both convolution and block coding based on the proven AMSAT OSCAR-40 satellite's FEC telemetry model, and modified where necessary. If we start with a base 256 byte (2048 bit) data frame, once it has passed through a pair of RS(160,128) encoders, the scrambler, the convolution encoder and the interleaver, we have 5200 bits to transmit. Thus, ignoring pre- and post-amble, each data frame will take 4.3s to transmit.

Each frame consists of a 2-bit satellite id and a 6-bit frame type indicator then 440 bits of real time data followed by 1600 bits of payload data. This results in the required total frame size of 2048 bits (256 bytes). This also fixes the frame transmission rate to one frame every five seconds.

```
  _____
 /_____/_____/_____/_____/|
 |satid  |ftype  |rt-tlm|  data    ||     2048 bits (256 byte) Frame
 |__2 ___|__6____|_440__|__1600__|/
```

Sat Id

The first 2 bits are the Sat Id currently defined as:

[0][0] = FUNcube 1
[0][1] = FUNcube 2 on UKube-1
[1][0] = unallocated
[1][1] = Extended protocol (look elsewhere for the Sat Id!)

Frame types

The next 6 bits will be transmitted MSB first and will indicate one of three main frame types, also which frame in the overall transmission sequence is currently being sent.
Main frame types:
- Whole orbit data (type = WO)
- High resolution data (type = HR)
- Fitter messages (type = FM)

Real Time Telemetry
Although not a frame type in its own right (because it is included with all frames) the real time information sends the state of all channels from the EPS, RF, PA, antenna and software systems. Collection frequency is every 5 seconds.

Whole Orbit Data
This is the science bit, intended to provide all the information required for the Material Science Experiment. The data will be sampled once per minute for 104 minutes. The main focus of the data is the four analogue temperature readings sampled at the full 12 bit resolution. These, coupled with the solar panel voltage and temperature readings, should be enough to conduct the experiment. Also included are the battery voltage, system current and solar current collected. These will be a good indicator of the overall power state of the satellite over the course of a whole orbit.

High Resolution Telemetry
The purpose of the high resolution data is to be able to look at the tumbling rate of the satellite. This can be calculated by looking at the output from each solar panel at a relatively high sampling frequency. Thus the data collected is the 5 sun sensors, together with the solar panel and battery currents, sampled once per second for one minute.

Transmission Schedule

The above data collection strategy results in:
- 12 Whole orbit frames
- 3 High resolution frames
- 9 Fitter message frames

UKube-1

The first spacecraft project being undertaken by the newly formed UK Space Agency will be UKube-1. This is being developed in collaboration between a number of SMEs and Universities.

UKube-1 will be a 3-U CubeSat and is now expected to be launched into a low earth orbit in early 2014.

Image © Clyde Space Ltd

The spacecraft will carry three experimental payloads and, additionally, AMSAT has provided a set of FUNcube boards. These will form the Educational Outreach that is part of the UKube-1 mission requirements and will also provide a redundant communications system for the satellite.

The MSE on UKube-1 consists of four strips - two just like FUNcube-1 and two made of titanium - one simply polished and one with a black PVD finish.

In addition to the FUNcube payload, the other UHF/VHF radio transceiver that is being used on UKube-1 also has a "loop back" mode of operation available for use after the end of the main mission. This mode provides a 'bent pipe' FM to DSB single channel transponder for amateur use.

To avoid confusion with the existing FUNcube-1 spacecraft they are using the term "FUNcube-2 on UKube-1" to describe this part of the FUNcube Project.

Transponder uplink   435.080 to 435.060 MHz
Transponder downlink   145.930 to145.950 MHz
Telemetry beacon   145.915 MHz

AMSAT-UK

Prospective new members can find out quite a lot about AMSAT-UK by visiting our web site at http://www.amsat-uk.org where they can find out about the aims of the organisation, check on the committee and our publication, Oscar News, and join online.

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