Design of a small satellite UHF identification and TT&C radio beacon

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The increasing number of satellites within the low earth orbit space environment has led to an increase in unknown small satellite failures, problems in identifying individual satellite during a cluster launch and difficulties in tracking for space monitoring stations. This project will investigate a self-contained radio beacon that can transmit a satellite identification tag with basic telemetry data which will provide a capability to identify the satellite, provide on-orbit fault finding, an alternative control communications pathway and a signal that could be tracked from multiple ground stations. The aim of the project is to provide a radio beacon design and ground tested prototype that integrates existing technologies and systems. The preliminary investigations into an operational system has produced a breadboard-based solution that indicates that the development of a radio beacon for use in a space environment is a feasible project. The application of this system on a small satellite will help to decrease the current satellite failure rate, provide an on-orbit fault finding and correction capability and an increased space situational awareness in the low earth orbit environment.

Contents

Nomenclature

Variables:

c	=	speed of light	[299,792,45 m/s]
d	=	path distance	[m]
f	=	radio frequency	[Hz]
G_{rx}	=	Receive antenna gain	[dB]
G_{tx}	=	Transmit antenna gain	[dB]

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Terms, Abbreviations and Acronyms:

APM	=	Arduino pro mini
CMOS	=	Complementary metal-oxide semiconductor
c-Si	=	Crystalline Silicon
EEPROM	=	Electrically erasable programmable read-only memory
FPGA	=	Field-programmable gate array
FSPL	=	Free-space path loss
GaAs	=	Gallium-Arsenide
IDE	=	Integrated development environment
ISM	=	Industrial, scientific and medical
LDO	=	Low dropout
LED	=	Light emitting diode
LEO	=	Low earth orbit
LPWAN	=	Low-power wide area network
LTE	=	Long-term evolution
NASA	=	National Aeronautics and Space Administration
P2P	=	Point-to-Point
PCB	=	Printed circuit boards
RF	=	Radio frequency
RX	=	Receive
SSA	=	Space situational awareness
TASC	=	Triangular advanced solar cells
TX	=	Transmit
TT&C	=	Telemetry, tracking and control
USB	=	Universal serial bus

I. Introduction

The reduced cost of designing, manufacturing and launching a small satellite has led to an increased number of small satellites being launched into the Low Earth Orbit (LEO) space environment[1]. The ability to ride-share a launch vehicle has reduced the cost of launching a small satellite into a LEO orbit but has led to a reduction in space situational awareness (SSA) due to upwards of 100 small satellites being launched from the same launch vehicle in a small-time frame[2]. This single platform, multiple satellite launch produces difficulties in identifying an individual satellite amongst the cluster from the ground monitoring stations which can result in problems with creating a communication link with the individual satellite[3]. The standardisation of small satellite manufacture has reduced the cost of production allowing government, educational and commercial entities to create and produce small satellite designs to meet their own requirements. The development and design process for each satellite has resulted in a 55% failure rate for academic institutions and a 23% failure rate for commercial industry[4] with the cause of failures being unknown or reduced to a small number (5-10) of possible causes. The inability to control or track a space object and provide full SSA within the LEO area increases the risk of a collision for all users of the LEO space environment with a collision between two objects in space resulting in a larger number of smaller space debris objects leading to an exponential risk of further collisions between objects, which is known as the Kessler Syndrome[5]. Providing a communication sub-system that is independent of all other systems on a satellite will allow the satellite to be identified and tracked regardless of the failure of any other satellite systems. The purpose of this project will be to design a self-sufficient, independent communication system that can transmit identification and basic telemetry data to multiple ground stations that can track the satellite by its radio frequency (RF) signal. This allows identification of an individual satellite during a single platform, multiple satellite launch providing greater SSA and reducing the risk of collisions with space debris for satellite and pass through operations in the LEO environment. The beacon will provide a UHF communications system that can provide identification and telemetry data for satellite on-orbit fault finding to facilitate determination of causes of failure to reduce the chance of failure for future launches and operations. This system will have the capability to be extended to include a ground monitoring system capable of tracking the small satellites and to provide an alternative communications system that can have limited control of the other satellite systems to offer a redundant system to correct on-orbit failures that prevent operation of the satellites primary communications systems.

II. Aim

The aim of this project is to produce a design and ground tested prototype for a self-sustained communication platform that is independent of the existing satellite systems and can provide satellite identification, basic satellite telemetry and control data through a periodic radio frequency beacon transmission that is capable of being tracked utilizing multiple geographically dispersed ground receiving stations. The communications beacon will be able to operate as a separate system with its own independent power source, computer processor and radio providing information to the ground station regardless of a failure in any other system on the satellite for the length of a typical LEO small satellite mission (between 8-36 months). The primary focus of this design will be to provide an individual satellite with a unique RF identification for ground station monitoring equipment to a identify a satellite after a single platform, multiple satellite launch and provide a mechanism in which space monitoring organisations can perform SSA analysis of the LEO environment without using resource expensive radar and optical monitoring equipment. There is scope to use the radio beacon to provide basic telemetry data to allow for investigation of possible causes of failure for on-orbit post-failure analysis and rectification. This system can be further enhanced to include a receiving function that allows an alternative pathway for executing a control command if primary communications with the main satellite system is lost. Multiple ground receiving stations can be used to estimate the position of the satellite by analyzing the time of arrival and frequency differences to provide full a tracking capability for the operators or space monitoring organisation.

III. Project Scope

The UHF identification and Telemetry, Tracking and Control (TT&C) radio beacon will be broken down into four separate sections, solar power generation, power storage and regulation, computer processing and radio communications. The project will leverage and integrate existing technologies for each section to produce a fully independent and self-sustained radio beacon system for application on a small satellite platform.

IV. Literature Review

The review will be divided into 6 sections for this project with the first section verifying the requirement for this system, the second being a review of existing research and systems of the same or similar functions and the remaining four sections for each individual sub-system of the radio beacon (Solar power generation, Power storage and regulation, Computer processing and Radio communications).

1. Requirement for an independent Identification and TT&C system

The standardisation of small satellite design, construction and launch has reduced the cost of manufacturing and launching a small satellite into a low earth orbit which has led to the number of small satellite missions increasing from 20 missions in 2011 to 322 in 2018 with the number estimated to increase to 300 missions in 2019 and between 2000 to 2800 missions to be launched in the next 5 years[6]. A small minority of these planed missions will be delivered to LEO using dedicated launch vessels but most of the satellite are expected to utilize the current rideshare or piggyback launch vessels[7]. The Indian Space Research Organisation released 104 small satellites into LEO during a 12-minute cluster release from a single launch vessel on the 15th of February 2017[8], which provided a demonstration of the ability for a cluster launch but also presented the problem of identifying a singular satellite within the launch cluster. Early identification and communication with the satellite and the ability to provide multiple pathways to correct system error or faults provides a good determination of mission success[9].

The 55% and 23% failure rate of the previous small satellite missions can be contributed to some common faults such as communications systems failure, power system failure, Bus system or payload interface failures, deployable component failure, failure of components (due to quality, inadequate documentation, limited testing) or system failures due to delays in launch (system degradation). When the satellite fails on launch or in orbit then the exact determination of the cause of failure is difficult to ascertain as the communication link with the ground station is often non-functional preventing satellite telemetry data from being received. The provision of a system that provides telemetry and satellite state data to the ground station irrespective of a failure of any satellite sub-system provides information that can be used to either determine the cause of failure or help reduce the number of possible causes of failure. When the cause of failure is identified or the number of possible causes of failure is reduced then this information can be used to reduce the incidents of full or partial failure in future small satellite missions reducing the failure rate of small satellites.

If the cause of failure is diagnosed whilst the satellite in on mission from the provided telemetry data, then there remains the possibility that an on-orbit rectification could be carried out and the mission can be completed or partially completed. The on-orbit rectification will require some sort of communication path to the satellite to be able to carry out any command to bring the affected system back to a serviceable state. If an emergency communication system has not been provided with the satellite system, then this radio beacon could be utilized to provide minor control of the satellite systems via an alternative communications link.

2. Existing systems and research

The existing available systems include the CUBIT system from SRI international[10], the SOARS system developed by TIGER innovations, a passive RF tag being developed by Stellar Exploration inc[11], the HyELT system proposed by M42 technologies, a radio beacon designed for the IRASAT1 cube satellite[12] and a safety radio beacon developed by University of West Bohemia[13].

The CUBIT, SOARS and passive RF tag deliver a similar capability in which an RF signal is used to deliver an identification to a ground-station to uniquely identify a satellite but are unable to provide any telemetry data or any control of the satellite.

The safety radio beacon developed by the University of West Bohemia is an on-board capability to provide satellite telemetry in normal and emergency (satellite failure) situations in the 433MHz range. This system provides only telemetry information whilst neglecting satellite identification, tracking and control and operates in an RF band that is subjected to congestion and RF signal detection degradation.

The HyELT system proposed by M42 technologies is similar in concept to this project in which it provides a transponder for uniquely identifying a satellite as well provide satellite health and state data. This project will provide a better solution as it allows for an alternative control pathway for the satellite as well as provide a system by which all satellites may be tracked from a series of ground stations.

The radio beacon designed for the IRASAT1 cube satellite provides similar capabilities to the HyELT system and this project but the radio utilizes the congested VHF radio band using a licensed band of frequencies resulting in this project providing a more robust and easily implemented solution.

There exist a few systems that identify a satellite using optical based systems such as the ELROI system being developed by Los Alamos national laboratory[14] and the LEDSAT system developed by the University of Rome[15] with the ELROI undertaking on orbit trials in 2018 with no success of positive detection of an optical identification tag[16]. The optical based systems can provide satellite identification but are unable to provide TT&C data making a beacon with an RF signal a better solution.

All the current systems in development either provide identification or satellite telemetry data via a signal that can be tracked but none of them provide a system that can include all these capabilities in one self-sustained system. This project will provide a radio beacon that can provide all of these capabilities as well provide scope to be further developed to include customizable telemetry data from the satellite systems as well as provide scope to be extended to include a control capability for on-orbit rectification of system failures.

3. Solar Power Generation

The two main types of solar panels available for use in a space environment are Gallium-Arsenide (GaAs) and crystalline Silicon (c-Si) based solar panel. The GaAs based solar panels have a higher efficiency (typically 22% to 28%) when compared to then the c-Si based panel (12% to 18%) for a single-junction which allows for a smaller surface area required for a fixed power requirement. The GaAs based solar panels have a slower degradation then the c-Si panel but as the average mission length is expected to be between 8-36 months, this will only be a small consideration when determining a final design for the power generation system.

The most prohibitive constraint on using the GaAs based solar panels is the high cost of manufacture, which requires that the c-Si solar panels be initially used for ground testing in the design of the system. The c-Si solar panels will be used in the hardware and software design phase to develop the power generation, regulation and storage systems. A solution for the type of GaAs based solar panels that could be used for this project will be investigated, built and ground tested to provide the final design for the power generation system.

The initial design for the power generation system will be based upon a LEO sun-synchronous orbit with an altitude of 500-600kms and an inclination of approx. 98° which results in an orbital period of approximately 90 minutes with a slant range of between 1000-2000kms. The conditions that may affect the power generation and that will need to be considered are the time the panels will be in full sunlight, the time the satellite will be behind the Earth or Moon, solar irradiance (in full sunlight, Umbra and Penumbra) , the attitude of satellite effecting the angle of the sun on the solar panels, the space environment (solar radiations, out-gassing, temperatures etc.) and tumbling of the satellite.

4. Power Storage and Regulation

The major consideration for power storage in this project is the additional isolation verification and testing requirements for any battery system installed on a satellite system. The launch providers requirements to verify the batteries ability to withstand all forces and vibration during the launch and maintain isolation from all other satellite and rocket systems in case of failure[17] determines that using a battery for this system will be an undesirable solution. The remaining solutions to be investigated are to not include a power storage system or to use a super capacitor energy storage system. If no storage system is installed, then the communications systems may not operate when the satellite is in umbra or Penumbra under low irradiance situations which can be minimized if the satellite remains in full sunlight conditions during a sun-synchronous orbit. If the satellite is to be operated in a polar orbit, then there will be a requirement to store energy for when the satellite is in low irradiance conditions which can be facilitated by an energy storage system using super capacitors. Super capacitors can contain no energy storage and begin to store energy after the satellite has been released from the launch vessel meeting the requirements of the launch provider as well as providing a system to store enough electrical energy to operate the radio beacon in low-irradiance phases of operation.

The existing low-dropout (LDO) regulators used for power regulation on the ground-based systems (LM1086[18] and MIC2505[19]) consume some power (up to 5mA) whilst regulating voltage with greater power consumed when regulating an increasing input voltage. An alternative LDO regulator or a buck converter system which consumes a lower quiescent current and provides greater voltage conversion efficiency will be investigated and tested for operation with this system to reduce the amount of power generation required to minimize the size of the solar power array and/or increase the available power for the system.

5. Computer processing

The major considerations for the selection of the computer processing sub-system are…

- The processing power, speed and memory (Flash and EEPROM) to handle the tasks required to collect, save and transmit the data
- Minimize the electrical power consumption of the sub-system to support low power operation
- Has a proven record of operation in the space environment with fast recovery after a power loss
- The processor and the operating system are well supported and resourced
- Ease of design, construction and initialization of the supporting hardware and software

The major systems investigated to meet the task required of the computer processing sub-system was the Raspberry PI, Arduino based microcontrollers, Teensy based microcontrollers and FPGA based solutions. The power consumption of the Raspberry PI is between 500mA and 1A[20] which is too high for this application and the PCB space requirements meant that it is not suitable solution for this project. The difficulty and lack of support for programming a FPGA array means that this solution was not considered for the initial development of this system. The Teensy based microcontrollers (AT90USB1286, MK20DX128 and MK20DX256) were considered appropriate tools for the system as they meets the processor and memory considerations but the power consumption (approximately 20mA for low power and lower clock rate Teensy2.0 and greater than 35mA for Teensy3.0 and above)[21] is greater than other options available for use.

The Arduino based ATmega microcontrollers were selected as they are open source with better support in terms of hardware and software design and have a proven history of operation at low clock speeds and low voltage reducing the power consumption. The ATmega microcontrollers were selected as the operating current is typically less then 5mA when operating on 3.3V with an 8MHz external clock[22]. The flexibility in the design of a processor system based upon an Arduino based ATmega microcontrollers and the existing resources available means that this solution is the best available for the initial design.

6. Radio communications

The major considerations for the selection of the radio sub-system are…

- Long-range communications (nominally 1200kms, but up to 2000kms)
- Low power consumption during all phase of operation
- Noise tolerance and reduction of interference including RF spectrum considerations
- Minimizing Antenna requirements
- Well supported system with a proven space heritage

The major available low power, long range communications systems that were considered for this application were SIGFOX, LoRa and NB-IoT. The SIGFOX and LoRa systems utilize the unlicensed ISM bands, whereas the NB-IoT system requires the use of the licensed LTE bands so the NB-IoT will not be considered a solution for this project. The main difference between the SIGFOX and LoRa systems is that the LoRa system can use point-to-point (P2P) communication whereas the SIGFOX uses a Low-Power Wide Area Network (LPWAN) to collect and distribute the data. The P2P communications protocol is considered a better option then the LPWAN as there will be no reliance or cost on utilizing a third-party infrastructure to collect the data and there remains greater flexibility in the communication system design and operation.

The LoRa radio module can operate in the 433MHz band (RFM98 model) and in the 915MHz ISM band (RFM95 model) with the latter being selected to be used as the spectrum contains less interference and a smaller antenna can be used. The LoRa radio module is controlled using existing software libraries for use with the Arduino or Visual Studio Code programs which allows for rapid development of software supporting the communications link. The HopeRF RFM95 radio module was selected as the data sheet indicates that the module is cable of operating at 3.3V whilst consuming between 20mA and 120mA during a transmission (for a TX power of +5dBm and +20dBm respectively) with a maximum link budget of 168dBm and a receive sensitivity down to -148dBm[23]. The LoRa has a demonstrated history of operations in a space environment and can operate over the distances required which will be verified through ground testing to ensure that the it will meet the link budget.

V. Project Management

The project management of this project will be based upon an Agile iterative development approach where the initial design will be produced after the research and design of each sub-system is done independently with the resulting sub-systems integrated to an initial prototype system. The hardware and software will then be subjected to continual production of protypes which are produced through a plan, design, check and adjust cycle. There is scope to deliver parts of the system during the iterative development cycle based upon incremental development project management techniques.

VI. Planned methodology

The initial development of the system will be based upon a relatively generic set of orbital parameters for a small satellite mission to develop each individual sub-system. The sub-systems will be integrated and tested as a breadboard-based system that will enable rapid development and prototyping. This will allow timely feedback to guide the next stage of iterated development of the system hardware and software until the design meets the specifications of the generic satellite mission. Once the initial parameters of a generic small satellite mission are met, the system will be designed to operate in a space environment to meet the parameters of a current small satellite mission to determine the viability of the system. A full operating radio beacon system with be designed and constructed on a printed circuit board (PCB) using components that can successfully operate in a space environment which will be subject to a series of ground-based testing. The PCB system will be subjected to the test, evaluate, analyze, redesign and construct cycle until the final radio beacon communication system design is completed.

VII. Timeline for completion

The project management methodology selected for this project is not a traditional waterfall technique but based upon an agile project management technique. The goals of the project will be broken down to major and minor deadlines that are constantly evaluated and adjusted to suit the progress of the project. The milestones are detailed in the GANTT chart in appendix A.

VIII. Current Progress (Work completed to date)

Before any development of the system was carried out the major orbital parameters of a generic small satellite LEO mission that will affect the communication systems were determined to use as a guide to produce the initial system design. The mission orbital parameters were determined from a sun-synchronous orbit, with an orbital height of approximately 400-500kms and an orbital inclination of 98°. These parameters result in an approximate minimum slant range of 1000kms and a maximum slant range of 2000kms. The orbital period is roughly 90 minutes with the view window of each pass being in the region of 8-10 minutes. The orbital parameters that will be used after the initial design for full testing of the system will be determined from using a ground station located in Canberra, Australia against the two main orbits used for small satellite missions. The most common orbits for a small satellite mission are a sun-synchronous orbit with an orbital height of 300-400kms and inclination of 52° or a sun-synchronous orbit with an orbital height of 500-800kms and inclination of 98°[24].

The initial software program design will be based upon a periodic cycle that repeats on an infinite loop until a command is sent to cease operation or at the conclusion of the mission. The microcontroller initializes once power is applied to the system after deployment from the launch vehicle then shuts down the radio and itself for a period of 45 minutes to prevent any RF transmission to meet the specifications of the *NASA launch services Program, program level dispenser and CubeSat requirements document*[25]. The system will run on a periodic loop (refer Figure 1) where data is gathered and transmitted, the radio then has a receive period of 30 seconds to receive a command and finally the microprocessor and radio will enter a low power mode for a random period between 4-5 minutes to prevent synchronization between multiple satellites. This will allow at least 1 transmission during a satellite pass window and at most 2 transmissions whilst minimizing the power consumption of the radio and processor. A sample of the considerations required in the software are the use of EEPROM to maintain a

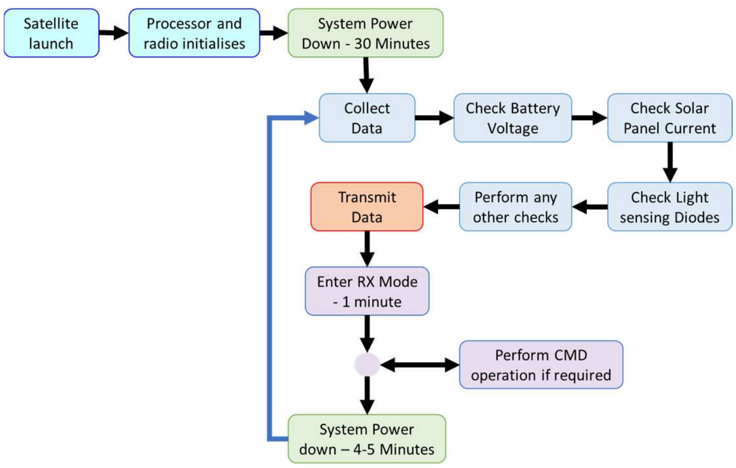

Figure 1 - Initial beacon software cycle

permanent record of the deployment from the launch vehicle, some form of encryption and authentication to prevent access to the control mode of the radio, a serial communication system to receive or transmit data from other satellite systems and ability to operate libraries that support the radio sub-system.

The initial investigation of the LoRa communication protocol was carried out utilizing the Adafruit Feather 32u4 LoRa Radio (RFM95) to become familiar with the system operation. This system contains a HopeRF RFM95, low power, long range radio transceiver module that is controlled by an Atmel ATmega32u4 microcontroller with contains 1kB of EEPROM and 32kB of Flash memory[26]. The system is programmed and powered via a USB connector with the power regulation carried out by the on board Low-Dropout voltage regulator. The initial testing showed that the processing and communication system were able to operate together using the Arduino integrated development environment (IDE) as the program development and loading tool for rapid software development. The processing power, speed and memory were found to be acceptable but the power consumption of the microcontroller, on-board LEDs and supporting peripherals was found to be over 200mA during a transmit which is too high to be used for this project. The Adafruit Feather 32u4 LoRa Radio would be an appropriate system to use for a ground receiving station but further investigations into alternative systems was required to determine an appropriate combination of components for the satellite system.

A separation of the processing and radio sub-systems was determined to be the best approach of investigating the power requirements of each system individually with the system broken up into the HopeRF RFM95 radio transceiver module and the Arduino Pro Mini (APM) module for the processing system. The APM is based upon the Atmel ATmega328p microcontroller will an operating voltage of 3.3V and a clock speed of 8MHz[27] which was selected over the ATmega32U4 model as it better supports serial communications[28]. The APM contains a CMOS based LDO power regulator (MIC5205) which will consume some power whilst regulating the input voltage, which can be minimized if the voltage used at the input is as close as possible to 3.3V and contains a power LED which consumes approx. 5-10mA of power. This combination of components can be modified to be fitted to a standard breadboard which allows for rapid prototyping of each sub-system and ease of integration with the power generation and regulation sub-systems. Minimizing the current required to operate the processing system will allow a greater percentage of the fixed current generated by the solar power system to be dedicated to the radio system which will allow the TX power to be increased providing a better communications link budget.

One of the biggest determinations of the validity of this project was to determine if there was a low power, long range communications protocol available that will allow communications of small packets of data over the expected range. The free space path loss (FSPL) is the major loss component and determinant of the communications link budget with components of the equation being,

$$FSPL = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{C}\right) - G_{tx} - G_{rx} \qquad (1)$$

where d is the slant range, f is the radio frequency, c is the speed of light, G_{tx} is the gain of the transmitting antenna and G_{rx} is the gain of the receiving antenna. Using the radio frequency 915MHz, over the generic slant range 1000-2000km with the transmit and receiving antennas having a typical dipole of 2.15dB in equation (1) results in a FSPL of between 147dB and 153dB for the generic orbital parameters. The RFM95 LoRa radio transceiver can transmit at 20dBm using 100mW RF output power and has of a maximum receive sensitivity of -148dBm dependent on the modulation type and spreading factor selected. If a TX power of 10dBm is used, then the approximate received signal power will be -143dBm based upon the communications link budget for 2000km which can be achieved by the RFM95 radio. These nominal figures allow the HopeRF LoRa RFM95 radio transceiver to be used in this application but will require further ground testing utilizing attenuators in the antenna path to verify operation over the expected distances.

The other major consideration for determining the validity of this project is the power generation system can support the power regulation, computer processing and radio communications sub-systems power requirements. This required an analysis of the power required by each sub-system by placing a small resistor in series with the modules and measuring the voltage across the resistor to determine the current draw of the sub-system during operation. A variety of resistors were used (0.47Ω,1Ω,10Ω and 20Ω) to determine an average current draw to improve the accuracy of the measurements. The power requirements of the processor were measured by cycling the APM module through the power on mode and the five power saving modes available in the *lowPower.h* library using a variety of regulated and unregulated voltage levels. The power requirements of the RFM95 module were determined by running through three checks which analyses the current draw level and length of time dependent on the radio mode, the Transmission power and the transmission packet length. The testing procedure and results for each of the power checks are detailed in appendix B.

Average current measurements for APM module power modes					
Input Voltage and resistor	3.3V - Vcc pin - 1Ω	5V - RAW pin - 1Ω	3.3V - RAW - 1Ω	3.3V - RAW - 10Ω	3.3V - RAW - 20Ω
power on current (mA)	13.78	50.67	13.51	14.66	14.40
powerDown current (mA)	10.00	42.25	10.00	11.43	11.94
powerSave current (mA)	10.00	42.30	10.00	11.43	12.10
powerStandby current (mA)	10.41	42.59	10.09	11.53	12.20
powerExtStandby (mA)	10.41	42.54	10.09	11.53	12.20
idle (mA)	10.90	46.15	10.58	11.94	12.50

Table 1 - APM module average current measurements for each power mode

The results from the processor power mode checks show that the built-in voltage regulator on the APM module and the power indication LED is a major consumer of current during operation of the processor is. The on-board voltage regulator (MIC5205) and the LED consumes 5mA to 10mA of current when the Arduino is being powered by a 3.3V voltage source and when the input voltage is increased to 5V then the corresponding current draw increases by 300%. This shows that further investigation into a suitable voltage regulator for the project is required to minimize the power consumption of the whole system. If the 10mA voltage regulation current is removed from the processor power mode checks then there is a large decrease in processor power consumption. The largest power consumption saving is gained when the processor is put into *powerDown* or *powerSave* mode and these modes will be used when there is no processing required in the software cycle. The main consideration required when using these modes of operation for the processor is to consider the time required to "wake up" from the power saving modes before performing the next operation when designing the software cycle.

LoRa power mode current measurements			
Series resistor value (Ω)	1	10	20
Sleep current (mA)	0.70	0.62	-0.09
Recieve current (mA)	11.00	10.00	11.67
No data transmit current (mA)	2.00	2.00	4.40
Idle current (mA)	2.00	2.00	2.00

Table 2 - RFM95 LoRa module average current measurements for each power mode

The results from the radio power mode checks show that the maximum power saving can be gained when the radio is put into sleep mode when it is being not used and minimizing the time the radio is in receive mode. The most expensive mode in terms of current draw is when the radio is in receive mode (10mA) with the radio in transmit or idle mode being the second worst (2mA). Putting the radio into sleep mode draws as little as 0.7mA and can reduce the power consumption, which allows for more power to be stored in the 4-6 minutes when the system is in the low power software cycle. If the radio sleep mode is selected whenever the radio is not required, then the wake-up time will have to be considered before moving into the next stage of the software cycle. There is a sharp increase in current from 10mA to 80-120mA when the radio mode transitions from receive mode to transmit mode which will require further investigation when the full beacon cycle is developed to determine if the spike is due to changing from the receive mode or changing to transmit mode.

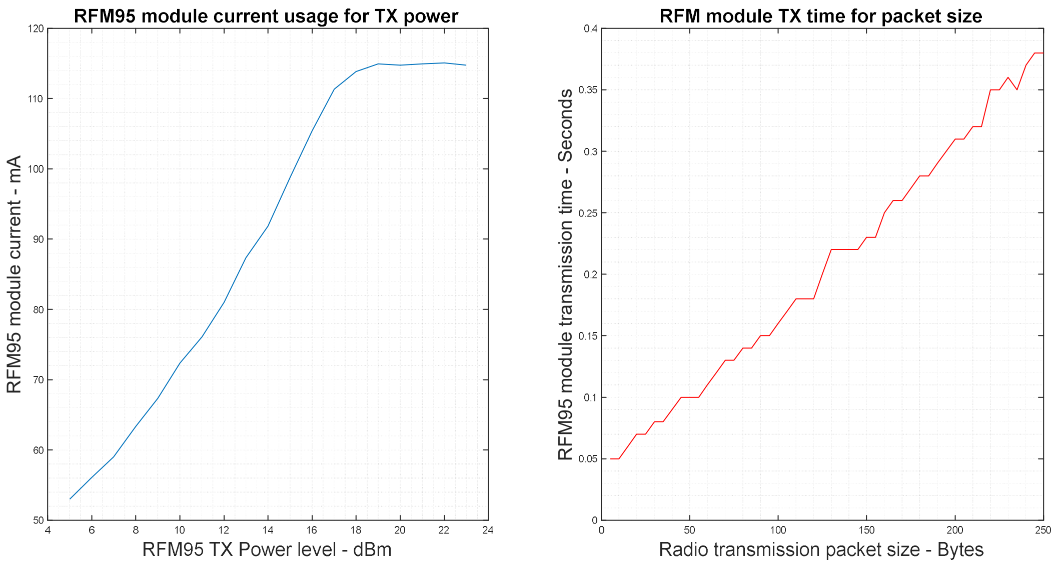

Figure 2 - RFM module TX Power current and TX packet size time measurements

The largest determining factor of the power consumption of the system is how much current is consumed and for how long when the RFM95 module is transmitting packets of data. The results from the TX power checks in Figure 2 show that the minimum current draw for the transmission is approximately 50mA at 5dBm which increases linearly by 4-5mA for each dBm increase until 19dBm is reached in which the current draw of the radio plateaus at 110mA for 19-23dBm. Reducing the circuit RF path losses and increasing gain for the TX and RX antenna will minimize the TX power required for each transmission and minimize the current draw of the radio. The time taken for each transmission is dependent on the Byte size with the minimum transmission time (including preamble) being 50 milliseconds for 5 Bytes, increasing by approximately 10mS for every 5 Byte increase to 380ms for 250 Bytes. Minimizing the number of Bytes required per transmission will minimize the energy required for each transmission and reducing the overall power required by the system.

Estimated current consumption of the sub-systems							
Software phase	Cycle time (s)	Regulation (mA)	Processor (mA)	RFM 95 (mA)	Total current (mA)	supply voltage (V)	Energy required (Joules)
Collect Data	5	5	40	0.2	**45.2**	**3.3**	**0.7458**
Transmit Data	0.1	5	10	73	**88**	**3.3**	**0.02904**
Receive Command	60	5	10	11	**26**	**3.3**	**5.148**
Low Power mode	300	5	1	0.2	**6.2**	**3.3**	**6.138**
						total	**12.06084**

Table 3 - Estimate current consumption of the beacon subs-systems and total energy requirement

Using the beacon software cycle in Figure 1with the sub-system power results in appendix A, the estimated current consumption of the radio beacon and each sub-system during software cycle was determined (refer Table 3 The estimation was based upon the maximum low power mode time and transmitting a 50 Byte packet size with a TX power of 10dBm. The results show that the maximum current draw is 88mA during the cycle, but this does not include any spike in current when changing between the radio modes which will have to be tested during the full beacon software testing. The time taken for one full software cycle is 365.1 seconds with the total energy required during one cycle being 12.06 Joules, refer Table 3 for the calculation.

A ground-based solar power generation and regulation system was constructed using three monocrystalline silicon solar panels manufactured by Seeed Studio with the dimensions 10mm x 55mm x 3mm that typically produced 100mA at 5.5V feeding a LM1086 3.3V, 1.5A LDO regulator. A reduced duration software cycle was created to run through the modes of operation as per the beacon software cycle with the cycle taking seconds instead of minutes to check the operation of the solar power system when transmitting 50 Bytes of data at 10dBm. Three solar panels connected in parallel was able to support the power requirements of the feather 32U4 LoRa system in direct full sunlight. When the solar panels were reduced to two solar panels, the system was able to support the initialization, data collection and transmission portion of the software cycle but the spike in current during the data transmission causes the processing system to reset with the data transmission being successfully completed. When the solar generation system was reduced to one solar panel then the system initializes and performs the data collection with the system resetting whilst attempting to unsuccessfully transmit the data.

Software cycle	3 Solar panel current	3 panel regulator current	2 Solar panel current	2 panel regulator current
Initialisation (mA)	81.65	84.35	78.56	81.58
Launch (mA)	13.67	13.67	11.10	11.10
Collect Data (mA)	16.32	16.32	16.32	16.32
Transmit data (mA)	76.70	76.70	74.15	74.15
Receive mode (mA)	27.13	27.13	24.86	24.86
low-power mode (mA)	13.34	13.34	11.10	11.10

Table 4 - Solar power generation and regulator current measurements

The same configuration of solar panels was utilized with the APM and RFM95 modules on the breadboard prototype with the system able to operate successfully using 2 and 3 solar panels for a TX power level of 10dBm in full and partial sunlight. When the system was reduced to one solar panel then the system was able to initialize but not transmit the data in full sunlight and not initialize in partial sunlight. Multiple values of capacitors (10µF, 100µF, 200µF,470µF and 1mF) were connected in parallel to provide additional current when the radio transmits, and the system was able to partially execute the transmission, but the microprocessor still entered the reset mode. The capacitor provided the current required for the data transmission, but it also drew the same amount of current from the solar panels restricting the available power to the microprocessors and radio. The results in Table 4 show that the current provided by the solar panels was less than the values from the manufacturer datasheets and the current that is consumed by the LM1086 regulator is between 2mA to 3mA.

Possible solutions to decreasing the amount of current required to be generated would be to use higher gain antennas to reduce the TX power requirement, isolating the power to the processor so that the radio TX current spikes does not cause the processor to reset, further investigation for an alternative voltage regulator to reduce current load on the solar panels, using alternative solar panels and using a super capacitor in a battery like configuration to provide additional current during transmission. The datasheet for a 10F super capacitor indicates that it can store 36 joules of energy which will allow 3 cycles of beacon operation whilst increasing the capacitor to 50F increases the storage to 180 joules or 15 cycles of operation.

The initial investigation of using a GaAs based solar panel has found two possible solutions to meet the power requirements of the project with the first being a Triangular Advanced Solar Cell (TASC) manufactured by Spectrolab[29] and the seconds being a Solar Wing panel manufactured by TrisolX[30]. The TASC design can produce 28mA at 2.19V max power per panel for a rectangular size (2 panels) of 15.5mm x 31.8mm, this would require a total of 8 panels to produce 112mA at 4.4V with a total surface area of 32mm x 62mm. The Solar Wing design can produce 29.2mA at 2.33V max power per panel for a rectangular size (2 panels) of 8mm x 50mm, this would require a total of 8 panels to produce 120mA at 4.66V with a total surface area of 32mm x 50mm. The Solar Wing design requires less surface area to produce slightly larger current which indicates that it is a better solution but both panels will require further investigate before a panel is selected for testing. The selection of a solar panel and associated design solution will be dependent on the inclusion of an energy storage system as well as the final power budget required to achieve the communications link budget and data length.

The processor and radio sub-systems require a DC voltage of 3.3V with the processor being susceptible to damage due to fluctuations in the supply voltage, which requires the use of a stable voltage regulator. The initial power regulation has been provided by either the APM module inbuilt MIC5205 LDO regulator or an external LM1086 regulator from Texas instruments in which both have shown the consumption of a significant portion of the current produced by the solar panels (between 2 and 10mA). An investigation into using an alternative low quiescent current LDO voltage regulator such as the LM2936[31], LT1763[32] or TPS78233[33] to reduce the overall power consumption of the system will be beneficial. An alternative approach to voltage regulation could be to use a low power draw buck-boost converter (such as LM3671[34]) which requires minimal quiescent current and as a result will have a low power consumption at a cost of an increase in circuit components and PCB board space.

IX. Future work

The following list is a sequential list of tasks that are to be carried out to meet the deliverable requirements of this project. The items highlighted by an Asterix are tasks that can be done without completing a previous item

1. Investigate and develop a low quiescent current, 3.3V voltage regulation subsystem
2. Calculate a detailed communications link budget for the minimum and maximum slant range and investigating the best communication software settings for the RFM95 LoRa radio module
3. Develop an expected electrical power budget based upon an optimized (TX power and radio packet size) communication link budget and the beacon software cycle
4. Construct a breadboard prototype integrating the designed power generation and regulation system
5. Test and evaluate the current draw of the voltage regulation, processing and communication sub-systems operating on the silicon-based solar panels
6. Investigate (and develop if required) a power storage system*
7. Investigate and integrate a transmission antenna*
8. Investigate and design a GaAs based solar power system*
9. Develop a full acceptance testing plan for breadboard model (including but not limited to power dropout checks, power consumption measured and minimized, ability to receive command, error in data minimized, Link budget check, low-irradiance checks) *
10. Develop and construct a full breadboard prototype including antenna and peripheral systems (battery check, solar panel current checks, photodiode checks, serial connection checks)
11. Develop initial full software cycle (including peripherals) for operational use and testing*
12. Full software cycle tests including attenuation equivalent to link budget path losses
13. Develop full acceptance testing plan for PCB model (including but not limited to launch RF silence time confirmation, confirmation of ability to turn radio off, verification of ability to receive data, shakedown tests, total power consumption test, cyber security checks, power shutdown and restart checks, Day-in-the-life testing, thermal testing, satellite tumbling testing, ground station communication testing)*
14. Selection of PCB components for operation in a space environment (solar radiation, vibration, temperature ranges, max power ranges, etc.)
15. Develop initial PCB design and prototype for the 1st Build, Test, Evaluate and Redesign cycle
16. Repeat previous step until final design and a ground-tested prototype deliverable is achieved

The design of the small satellite UHF identification and TT&C radio beacon provides point to point identification and telemetry data, minor satellite control and a RF source for tracking for a singular satellite. This system can be expanded to be fitted to all small satellites and provide a full tracking system to enable complete small satellite SSA in the LEO environment regardless of failure of the satellite. An extension of this project will allow one or more of the following to be completed in conjunction with the system that is fitted to the satellite…

1. A complete identification system of small satellites operating on a single frequency for LEO SSA monitoring by government and non-government organisations (commercial, academic and amateur operators)
2. Provide an alternative pathway for control of the main satellite systems with in-built cyber security
3. Provide a full receive capability for interrogation of satellite telemetry or to provide an additional RF transmit for tracking purposes
4. Deliver a fully tested system ready for operations in a space environment
5. A monitoring system of multiple ground stations using calculations of the time of arrival and frequency comparation of the received RF to provide tracking information for all satellites with this system installed
6. Provide a conceptual design for a publicly contributed ground monitoring system providing real-time tracking of all small satellites similar to the Flightradar24 or Flight Tracker system

X. Conclusions

The initial research has that a feasible system can be developed integrating existing technologies and systems that will provide an identification and TT&C radio beacon for a small satellite in LEO. The results of the power consumption checks of each individual sub-system demonstrates that a system operating an Arduino based processor and a HopeRF RFM95 LoRa radio module on regulated power generated from a solar source is a feasible design for the radio beacon. The communications link requires further investigation and testing to demonstrate that it can operate over the expected distances, a design for a solar panel array that is capable of operating in a space, a more efficient power regulation system design and a possible energy storage system design are required to be investigated before the initial PCB design and prototype of a UHF identification and TT&C radio beacon can commence.

XI. Recommendations

It is recommended that the project continues as per the planned methodology using the timeframes detailed in the GANTT chart (appendix A). The project should be extended to include the first 4 extension items detailed in the future work section as additional deliverables as these items are very closely aligned to the development of the space segment of the radio beacon. Developing these 4 extensions with this project will require much less resources to integrate, then if these system extensions were developed in a separate project as there will be much less cost in terms of materials and human resources. The fifth and sixth extension item should be considered as an additional optional deliverable on this project (time permitting) as the system can leverage existing research that has been completed by this organisation allowing quicker integration of the research technology whilst using a smaller amount of resources.

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