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

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Well written abstract to be added here

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# Nomenclature

*Variables:*

*c* = speed of light [299,792,450 m/s]

*d* = path distance [m]

*f*= radio frequency [Hz]

= Receive antenna gain [dB]

= Transmit antenna gain [dB]

*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

# Introduction

The reduction in economic and resource costs of designing, manufacturing, and launching a small satellite has led to an increased number of small satellites being launched and operated in the Low Earth Orbit (LEO) space environment[[2]](#endnote-2). A greater number of objects in the LEO environment has resulted in a decrease in space situational awareness (SSA) and an increase in the number of space debris, which leads to a larger reliance on resource expensive ground station monitoring equipment to maintain situational awareness in the LEO environment. The reduced cost of launching a small satellite into the LEO environment is a result of releasing multiple small satellites from a single launch platform, this is commonly known as ride sharing. Ride sharing has resulted in upwards of 100 small satellites being released from the same launch vehicle in a small-time frame[[3]](#endnote-3). This has resulted in a reduction in SSA immediately after the launch of small satellites and throughout their operational life cycle because of difficulties in identifying individual satellites. The difficulties of identifying small satellites in the LEO space environment results in a greater demand on the limited ground-based optical and Radar monitoring resources to maintain a reduced SSA capability. The standardisation of small satellite manufacture has reduced the cost of production allowing government, educational and commercial organisations with little to no space mission experience to create and produce small satellite designs to meet their organisations requirements. The unique development and design process to meet these organisations requirements for each satellite has resulted in a 55% failure rate for academic institutions and a 23% failure rate for commercial industry[[4]](#endnote-4). The cause of a small satellite failure is difficult to determine as the failure can reduce the amount of satellite telemetry data available for faultfinding. A deficiency of telemetry data can result in the determination of satellite failure being contributed to several causes of possible failure (typically 5-10 possible causes). The ride sharing launch produces additional difficulties in identifying an individual satellite immediately after release by the ground monitoring stations which leads to an increase in failure rates due to difficulties in creating the initial communication link with the individual satellite[[5]](#endnote-5). A satellite failure can cause that satellite to be uncontrollable and/or difficult to track causing it to become a space debris object. An increased number of space debris in the LEO environment diminishes SSA which leads to an increased risk of a collision for all users of the LEO space environment.

To increase SSA in the LEO environment and reduce the small satellite failure rate a solution needs to be investigated that aims to provide better methods of obtaining satellite telemetry data and provide a cost-effective method of tracking satellites and space debris in the LEO space environment.

The purpose of this project will be to design a self-sufficient, independent satellite radio beacon system that can transmit satellite identification and telemetry data and receive control commands using a UHF radio signal that is capable of being tracked using multiple geographically dispersed, cost-effective ground receiving stations.

The satellite radio beacon shall primarily allow for the identification of an individual satellite during launch and its operational life cycle providing greater SSA which leads to a lower risk of collisions in the LEO environment. Multiple graphically dispersed ground mounting stations constructed using low-cost, commercially available components are to be utilised to track the satellites beacons radio signal allowing the existing resource intensive ground-based monitoring systems to focus on other LEO space objects. The beacon will have a secondary function that can provide telemetry data for satellite on-orbit fault finding to facilitate the determination of causes of failure. Determining the actual cause of failure as opposed to having several possible causes of failure is expected to reduce the number of failures in future launches and operations. This system can be extended to include an alternative communications pathway that can be used to provide limited control of the other satellite sub-systems to offer a redundant system to correct on-orbit failures. Correcting an on-orbit failure can result in regaining control of the small satellite reducing the number of space debris objects in the LEO environment.

# Aim

The aim of this project is to design and produce a ground-tested satellite UHF radio beacon prototype and a cost-effective ground monitoring station prototype that can sustain a communications link for the distances required of a satellite a LEO orbit. In order to achieve this aim, three aspects will be investigated, firstly the satellite radio beacon that is to be a self-sustained UHF communication system capable of operating independently of all other satellite sub-systems for the duration of the satellites operation mission (until deorbit). Secondly, the UHF communications link which must be able to support the reliable transfer of satellite identification and telemetry data up to 2000kms to support the operation and monitoring of satellites in the LEO space environment. Finally, the ground monitoring station which must be capable of capturing the satellites identification and telemetry data and recording the precise time of arrival (TOA) of the radio signal and its GPS location. The ground station should be able to pass on the captured data and measurements to a peripheral device for post processing.

# Background

\*CONDUCT MORE CURRENT LIT REVIEW OF EXISTING SYSTEMS\*

A review of the current systems available has shown that solutions are provided for individual aspects of SSA in the LEO environment, but they do not take a holistic approach to key parameters of a satellite telemetry, tracking and control (TT&C) system. The key parameters of a TT&C system are satellite identification, telemetry, tracking and control. There are several systems that provide only identification (CUBIT, SOARS, Passive RF tag, ELROI and LEDSAT) or only telemetry (safety radio beacon) and several which provide identification and telemetry (HyELT and IRASAT1). The existing systems delivers solutions to one or two parameters of the TT&C system which address either, but not both, problems highlighted in the introduction. The proposed project will implement solutions for all four key parameters of a TT&C system that will address both problems presented.

The major orbital parameters that will be used for this project is based on a generic small satellite mission in the LEO environment. The mission orbital parameters were determined from a sun-synchronous orbit, with an orbital height of approximately 500kms and an orbital inclination of 98°. These parameters result in the slant range between the satellite and ground station being within 1000kms to 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°[[6]](#endnote-6).

A key goal of this project is to ensure that the design of the ground monitoring station be carried out such that the costs, difficulty of construction and the difficulty in operating the equipment is minimized. The result of minimizing these components of the design will allow a broader spectrum of the general public to create their own ground monitoring stations. If the general public were to create their own stations, then this will be able to create a larger number of ground stations that are more geographically dispersed. This has a two-fold effect of increasing the footprint and reliability of the ground stations for better SSA as well as increasing the general public awareness and engagement in LEO space operations.

# The present study

The design of the small satellite identification and TT&C system will be broken up in three major components: the satellite radio beacon, the communication link and the ground receiving station. The satellite radio beacon will contain four sub-systems: (1) Computer processing, (2) radio transceiver, (3) System software and (4) Power generation, storage, and regulation. The communication link is a standalone component while the ground receiving station will be separated into five separate sub-systems: (1) Computer processing, (2) radio transceiver, (3) GPS module, (4) System software and (5) Positional calculation.

## Satellite Radio Beacon

The first major component of the system to be investigated is the feasibility of a satellite radio beacon that is a self-contained system and independent of all other satellite systems. Each sub-system of the radio beacon will be designed and verified to ensure that the beacon is self-contained and has no dependence on any other satellite systems with the major constraint for each sub-system being the electrical power requirements can be met by the power that is generated. The components used in each sub-system will be selected to ensure self-sufficiency, independence, cost-efficiency, ease of operation and weight minimization.

### **Computer Processor**

1. **Materials and Methods**

The first consideration for the radio beacon is to select a component for the computer processing that can provide the required processing power, speed, inputs, outputs and memory that requires the least amount of electrical power to operate. The solutions investigated for this project were a Teensy based microcontroller (MC), an Arduino based MC, a raspberry PI and a FPGA board with the 3.3V, 8MHz Arduino Pro Mini module (APM) being selected for the initial design. The APM was selected as it fit all the computer processing requirements, it has a proven space heritage, it is well resourced and can be operated with a low supply voltage and clock speed to reduce power consumption. The APM was tested by measuring the amount of electrical current required during the operation of the processor with the method of testing and results presented in Appendix A.

1. **Results and Discussion**



Table 1 - Average current consumption for APM module processor and built-in regulator

The results for the APM module processor testing are detailed in Appendix A with a summary of the results shown in Table 1. The results indicate that the current consumption of the APM module increases significantly if the supply voltage to the built-in regulator is increased from 3.3V to 5V. If the input supply voltage to the built-in fixed LDO voltage regulator is significantly higher than the output voltage, then there is a large increase in quiescent current consumed by the regulator. This increase in current consumption will need to be considered during the design of the power generation, regulation and storage system.

The ATMEGA32P processor current consumption measurements are higher than the documented values expected by approximately 10mA for all modes. It was found during testing that the APM module contained a green surface mount LED that constantly consumes up to 10mA when power is applied. The current consumed by the LED is constant for all modes of operation and as such can be neglected if factored into the results.

The results show that the current consumed by the APM module can be reduced significantly when utilising the power saving modes of the *lowpower.h* library. When analyzing the results, it must be acknowledged that when the processor was placed in *power on* mode that the processor was sitting idle and not carrying out any processing tasks so the result is the minimum current that will be consumed. If the ATMEGA328P is required to carry out any processor intensive tasks than the current consumption will significantly increase, with the processor datasheet indicating a current consumption of up to 50mA. The results show that current consumption of the APM module can be substantially reduced (~90% less current consumption) if the processor is powered down into one of the low power modes when computer processing is not required by the radio beacon. The most substantial current consumption reductions occur when the processor is changed to either *powerDown* or *powerSave* mode.

The initial testing of the Arduino Pro Mini with an ATMEGA328P processor operating with a 3.3V supply and an 8MHz oscillator shows it can be operated successfully whilst consuming minimal current. A computer processing solution based on the APM modules is suitable to be used in the design of the satellite beacon, but it is dependent on the satellites power generation, storage, and regulation sub-system.

### **Radio Transceiver**

1. **Materials and Methods**

The second consideration is to select a radio transceiver that is capable of long-range communications at appropriate data rates that has a low electrical power consumption during operation. A high tolerance to noise, interference and doppler shift will be required in the radio as well as minimization of the antenna requirements. The initial investigation found three solutions that met the requirements: The LoRa spread spectrum system, SIGFOX Low-Power Wide Area Network (LPWAN) system and the NB-IoT LPWAN system. The LoRa system was the selected medium for the initial design for it also provided a superior Point-to-Point communications protocol, greater software support and can operate in the 70cm (430MHz, RFM96 module) and 33cm (915MHz, RFM95 module) band radio spectrum. The RFM95 (915MHz) and RFM96 (437MHz) LoRa radio modules will be used for testing with the RFM96 module being the preferred option to maximize the antenna options for space operations and to utilize a portion of the radio spectrum allocated for amateur radio and amateur satellite use. The testing will consist of determining the current consumption of the LoRa radio module for the different modes of operation, different transmit power values and for different data packet lengths with the testing method and results detailed in Appendix B. The connection of the APM module with the RFM96 Lora radio module is shown in Figure 1 using a RFM9x Lora breakout board designed by Boyan Nedkov (<https://github.com/attexx/rfm9x_breakout_board>) on a standard solderless prototyping breadboard.

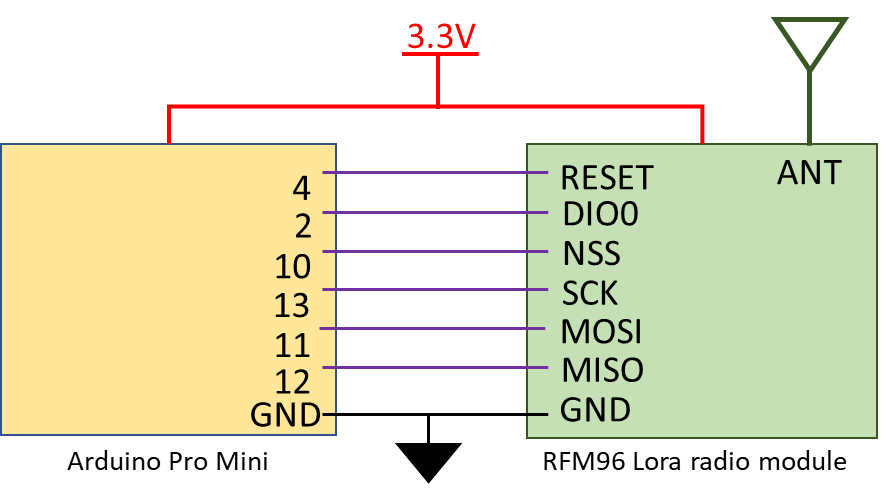


Figure 1 - Arduino Pro Mini and RFM96 LoRa radio module connection for testing

1. **Results and Discussion**



Table 2 - RFM96 LoRa module average current consumption for each mode of operation

The detailed results for testing the current consumption of each mode of operation for the LoRa radio module is in Appendix B with the measurements summarized in Table 2. The results show that the RFM96 LoRa module consumes the smallest amount of current when it is in *sleep* mode and the largest amount is consumed in receive mode (unless data is being transmitted). A large spike in current consumption of between 80-120mA was observed when the radio modes transitioned from *receive* to *transmit*. The results of testing the current consumption of the RFM96 LoRa module during each mode of operation shows that the radio is a viable candidate for use in the design of the satellite radio beacon if the current consumption is minimized. The current consumption can be minimized if the LoRa module is placed in *sleep* mode when it is not be utilized and the amount of time in *receive* and *transmit* mode is kept as short as possible to enable correct operation of the system. The transition from *receive* mode to *transmit* mode will not occur in the final form of the radio beacon software cycle and so the current spike will not be an inhibiter during normal operation.



Figure 2 - RFM96 module current consumption for Tx power level and transmission time for radio packet size results

The detailed results for the testing of effects of the transmit power and radio packet size for the LoRa radio module is in Appendix B with the summarized result of the measurements detailed in Figure 3. The current consumption for the LoRa module increases linearly (approx. 4.5mA/dBm) as the transmit power increases by 1dBm until 17dBm is reached in which the consumption plateaus at 117mA. The results indicate that the transmission time increases linearly by 10mS when the radio packet size increases by 5 Bytes when using the (0) default radio settings in the RadioHead library. The results show that if the transmitted power of the LoRa module and the size of the radio packets are reduced to as small possible then the current consumption of the radio can be minimized. The transmitted power of the LoRa module and the size of data being transmitted are the largest determinant of the current requirements of the radio, in which the final radio settings required will be determined by the testing of the communications link.

The initial testing of the LoRa module has indicated that it is a viable solution as the radio transceiver in the satellite radio beacon due to its ability to operate with limited current supply. The final radio settings (Transmit power and data size) determined during communication link testing and the satellites power generation, storage and regulation testing will verify if the LoRa radio can support the beacon operation through the totality of a small satellites operational lifecycle.

### **Software development**

1. **Materials and Methods**

The third design consideration is the software to be used which will be biased by the computer processor and radio transceiver selected with the software aimed to be no cost, well-resourced and uncomplicated to use. There is a large list of available software (Microsoft VSC, Atmel Studio 7.0, USBAsp. Win AVR, etc.) but the Arduino IDE software environment was selected for development due to the ease of use, portability to other platforms and number of resources available. The software flow chart and considerations for the radio beacons operational software cycle are shown in Appendix C.

1. **Results and Discussion**

The software flow chart in Appendix C was used to guide the development of the code using the Arduino IDE environment. The software program developed for the initial testing required 28% of the storage space (8758 of 30720 Bytes Flash memory) and the global variable required used 56% of the dynamic memory (1156 of 2048 Bytes SRAM). In the process of validating the code developed for the radio beacon cycle there were observed multiple instances of the radio data packets either not being transmitted by the beacon or received by the receiving station. It was found during the validation of the radio beacon software code that there were instances of data either not being transmitted from the radio beacon or not being received by the ground receiving station. This issue required further investigation utilising a Gqrx software defined radio receiver (SDR) driving an RTL-SDR dongle which determined that the data was being transmitted by LoRa module and the packets were being missed or dropped by the receiver. Further testing into the dropping of radio packets by the LoRa radio transceiver was carried out with the testing of the communications link.

The development of the software cycle was performed by using an iterative design approach where aspects of the software code was developed, tested, analyzed and redeveloped with this process found to be accomplished better in the Arduino IDE. The boot-loading, connection to different boards, built-in libraries, debugging properties and better resource availability for the Arduino IDE makes this an ideal environment for software development. The Arduino bootloader can take up to 2kBs of space on the Flash memory so if space does become an issue then an alternative software program can be used.

### **Power generation, storage and regulation**

1. **Materials and Methods**

The final consideration is to select a power generation, storage and regulation system that can support all the satellite radio beacon sub-systems during operation. Solar power generation is the only method considered to generate electrical power for this project due to the difficulties of operating other power sources (Lithium-ion batteries, hydrogen fuels cells, nuclear power, thermo-photovoltaic cells, etc.). The solar panel selected for ground testing is a 0.5W, monocrystalline silicon panel from Seeed which can produce a load output of 5.5V with a current of 90mA at 18% solar conversion efficiency. The energy storage system is expected to provide enough electrical storage to sustain operation during low-irradiance conditions in a space environment with a capacitor-based system selected for testing due to the launch isolation and ground testing requirements of a battery-based system. The electrical regulation system will be selected to minimize electrical current consumption with a variety of power regulators types to be tested.

A comprehensive description of all the power system testing methods and results are detailed in Appendix D with the first test conducted to measure the total electrical current requirement of the complete radio beacon to determine if the designed solar power generation system can support the operation of the beacon. The second test investigates methods of reducing the number and/or size of solar panels required to support the radio beacon operation. The current consumption of a variety of electrical power regulators will be measured during each phase of the software cycle in the third test to aid the selection of the regulator component in this project. The fourth test investigates the limitations of a capacitor-based energy storage system operating through the radio beacon software cycle. The final test will be to operate the satellite radio beacon for a 12-hour period using the components and configuration determined from the previous power tests as shown in Figure 2 to verify the feasibility of operating a self-contained, independent satellite radio beacon.

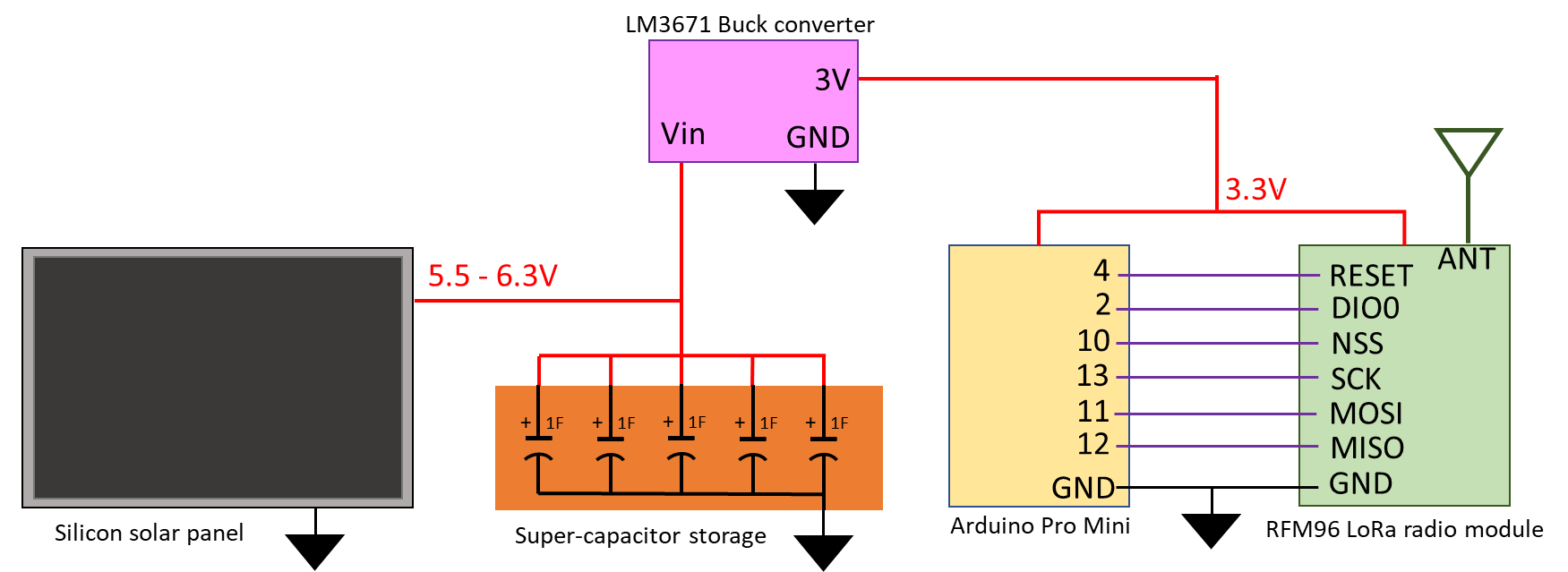


Figure 3 - Satellite beacon system configuration and connections for ground testing

1. **Results and Discussion**



Table 3 - Total current consumption measurements of the satellite radio beacon

The total current consumption of the satellite radio beacon for each phase of operation measured during the first test is summarized in Table 3 with the detailed results in Appendix D. The results show that utilising 2 or 3 solar panels can sustain operation of the Satellite radio beacon through all the phases of the satellite beacon operation. The beacon operation could not be sustained when a single solar panel was being utilised when transmit power level was set above 10dB without using an additional energy source. When 11mF of electrolytic capacitance was used to store additional energy to support the transmit phase then the radio beacon could be operated up to the maximum transmit power (23dBm) when connected to one solar panel.

The instantaneous current required at the start of the transmit phase of the satellite radio beacon software cycle is greater than the instantaneous current that can be supplied by a single monocrystalline solar panel. This spike in current consumption during the transmit phase results in a discontinuity in the power supply and a resultant reset of the system software cycle. To prevent a reset of the software system during the transmit phase, the current draw can be reduced, or extra supporting energy can be stored in an additional component (capacitor, inductor, etc) to support high transient currents. Five stabilizing 2.2mF electrolytic capacitors (11mF in total) in parallel with the solar panel allows for approximately 0.17 Joules of energy storage in the power system to smooth spikes in the current supply during peak usage. This extra energy being available in conjunction with the instantaneous energy being supplied by a single solar panel allows the radio beacon to be operated using the shortened beacon software cycle with the maximum transmit power (23dBm). Solar panels can generate 20% more electrical power in a space environment due to less atmospheric losses which provides a buffer against the reduction of generated power over time due to degradation of the solar panels.



Table 4 - Beacon total current consumption utilising different voltage regulators

The components used for the second test (regulator testing) were the APM in-built regulator (MC5205), a Low-Dropout (LDO) voltage regulator (LM1086), a buck converter (LM3671) and an ultra LDO linear voltage regulator (TS2904CZ). The summarized results are detailed in Table 4 which show that the LM1086 and TS2940CZ LDO regulators have a much higher current consumption then the MC5205 regulator and LM3671 converter during all phases of the software cycle. The inbuilt regulator and buck converter have similar quiescent currents throughout the software cycle except for during the transmit phase in which the LM3671 buck converter consumes 27mA less current.

The testing of the regulators demonstrated that the current consumption of the radio beacon can be minimized with the careful selection of regulation components. The results showed that the LM3671 buck converter consumes the least amount of current through the radio beacon software cycle. The APM module inbuilt regulator (MC5205) is also a viable solution if there is energy stored to sustain the radio transmit phase. The LM1086 LDO and TS2940CZ ultra-LDO voltage regulators will not be considered from the initial design but it is noted that the buck converter requires a minimal input of 2.7V to sustain an output while the LDO regulators require a substantially less input voltage before dropout occurs. If the energy storage system requires a lower dropout voltage level to maintain operation of the beacon for a longer period without any electrical power generation then the further investigation into the LDO regulators will be conducted.

\*look at some sort of capacitor testing graphs or tables\*

The initial check to verify that the super-capacitors could replace the electrolytic capacitors found that the radio beacon operation is supported through all phases of the software cycle, but the super-capacitors introduce a delay to the software cycle starting. If a single 5.5V,1F super-capacitor is used, then there is a 1 minute delay between when the solar panel start generating electrical power until there is enough energy to power all the subsystem with the delay increasing to 7 minutes when five super capacitors are used. The no-load charging time testing of the super-capacitors using one solar panel is detailed in Appendix D, with the results showing that the average time taken for five 1F super-capacitors to charge to full capacity when no load is connected is 24 minutes and 30 seconds using one solar panel. If two solar panel are connected, then the charging time decreases to 9 minutes and 20 second.

The average voltage potential of the super-capacitor storage system after a charging cycle was 6.3V which is 101 Joules of energy stored in the five capacitors. The super-capacitor system voltage potential throughout the software cycle after initialization and launch is displayed in Figure D3 in appendix D with the average operating time being 1 hour, 13 minutes and 43 seconds for one charge of the super-capacitor storage system. Discontinuities in the power supply would cause the Satellite radio beacon software to reset when the voltage potential of the super-capacitor storage system reduced below 3V which typically occurred during the transmit phase of the software cycle. The full charging characteristics of the super-capacitor system through the full software cycle of the satellite radio beacon system is shown in Figure D3 in appendix D when one solar panel is connected. The results show that there is an 8 minute and 20 seconds delay from when the solar panel first start to generate electrical power until there is enough energy to initialize the radio beacon hardware and software in which the voltage potential of the capacitors being measured at 2.6V. The super-capacitor storage system reaches it full electrical potential after 27 minutes of operation when the software cycle is approximately 19 minutes into the low power launch phase.

The super-capacitors tested were found to be suitable to support the operation of the radio satellite beacon at full transmit power with one solar panel connected. The testing revealed that there was an eight and a half delay between when power is first available from the solar panels to when there was power available to the satellite beacon through the regulator. This delay was due to the time it takes for the solar panels to charge the super-capacitors up to a usable voltage potential (~2.6V) with the delay being able to be factored into the time the satellite beacon is powered down after it is released from the launch vehicle. When the launch phase of the software cycle is complete, then the super-capacitor storage system voltage potential is at maximum when the beacon starts through its collect data, transmit, receive, power-down operational cycle. This cycle can then be maintained for over 70 minutes when no electrical power is being generated by the solar panels which equates to 78% of the excepted orbital period.

\*Full 12-hr operational check to be conducted\*

### **Summary**

A waterfall design approach for the development of the satellite radio beacon system led to each component of the system to be researched, designed, tested and verified in sequential order: Computer processing, Radio transceiver, software and power generation, storage and regulation. The cumulative results of the testing produced the initial design of the radio beacon (Figure 3) which can be constructed using a solderless breadboard and the initial software code as presented in Appendix C. The satellite beacon breadboard prototype was used to verify that the initial design meets all the previously stated requirements of the system with the next step in the design process being the verification of the communications link.

## Communications Link

The communications link between the satellite radio beacon and ground receiving station must be able to sustain the reliable transfer of data for the expected slant range for a satellite in LEO. The orbital parameters for the operational missions in the LEO environment determine that the maximum distance to be supported by the communications link is 2000kms which equates to a signal free-space path loss of 151.3dB.

### **Materials and Methods**

The first set of tests to be carried out for the communication link is to investigate the reasons the radio packets being dropped that was found during the software testing and determine if can be stopped or reduced. A detailed description of the methods used to carry out the testing is found in Appendix E with the tests first determining if changing the parameters of the RFM96 LoRa radio module or test conditions effects the number of packets dropped, which is known as the Packet Error Rate (PER). Secondly, a set of tests were conducted to analyze the data that is transferred to check if there are any Byte or Bit errors present in the transferred data. The last set of tests will utilize functions that monitor the quality of transmission and reception of data within the *RHGenericDriver.h* file that is inherited by the *RH\_RF95.h* file utilised in the RadioHead library.

The next step in the communication link testing is to verify the transmission power and radio settings that will allow for the reliable transfer of data to a satellite in LEO. The first step was to determine the resultant receiver sensitivity and link budget for the default radio settings and the two long-range radio settings available in the RadioHead library using the LoRa modem calculator tool available from Semtech. A transmitter and receiver LoRa module were then connected with a series of cables and attenuators which simulate the Free Space Path Loss (FSPL) to verify the results of LoRa calculator and that reliable transfer of data for the distance expected in an low earth orbit mission. The methods used for testing and the results is detailed in Appendix E with the results and current RF regulations used to determine the radio settings and transmit power that will be used for the final testing.

The final step in the testing of the communications link is to perform all the necessary calculations to determine the link budget and compare against the estimates of the LoRa modem calculator tool. The compete method of how the communications link budget was calculated is detailed in Appendix F with the results of the budget determining what transmit power level will be selected for the prototype testing.

### **Results**

The investigation into the radio parameters and test settings show that the two settings that record a reduction in dropped packets is the CRC setting and the coding rate. In general, when the CRC setting is turned on or if the number of CRC check Bits are increased then the number of packets dropped is reduced. If the CRC is turned on, then the number of packets dropped can be reduced by up to 50% and if the number of CRC check Bits are increased from 1 to 4 then the reduction in dropped packets by 75% was observed. This reduction in the number of dropped packets is not observed consistently throughout the different testing parameters and as such is just a general observation with no trend being able to be identified. There was a total of 8 tests carried out that analyzed the content of each Byte which found that there were no Bit errors presence in 79.904 Bytes received. Using the functions within the *RHGenericDriver.h* file revealed that the reason for the LoRa module not being received cannot always be determined. There were a total of 85 packets dropped when the CRC was on with 79 being determined to have errors and 6 not received at all and there were 12 packets dropped when CRC turned off with 3 packets determined to have errors and 9 not received at all.



Table 5 - RadioHead Library default LoRa module settings with LoRa calculator Bit rate and receiver sensitivity estimates

A summary of the RFM96 LoRa radio module configuration from the RadioHead Library default settings with a Bit rate and receiver summary estimate from the LoRa modem calculator tool is presented in Table 5. The initial table indicates that the 2 default settings could operate over a longer distance using a smaller portion of the radio spectrum with a comparable bit rate to the 3 default settings.



Table 6 - LoRa calculator Link Budget estimates and testing measurements for the RadioHead default settings



Table 7 - LoRa calculator transmission time estimates and testing measurements for the RadioHead default settings

The data presented in Table 6 and Table 7 compare the estimated data from the LoRa calculator against the measured data obtained from the testing for the link budget and transmission times. The results indicate that the LoRa calculator link budget estimates are a fair representation of the measured results, while the transmission times were slightly unreliable. The results from the testing reveal that the (2) radio settings can sustain a communication link for a larger distance (1dB greater attenuation in the FSPL) for a smaller transmit time ( 40% less Time-on-Air) than the (3) settings. The results from the testing also indicated that there is an approximate 20% increase in Bit energy (Eb) when comparing the 2 default settings against the 3 settings.



Table 8 - Link budget calculations for the satellite beacon to ground station communications link

A detailed method of calculating the link budget is presented in Appendix F and summarized above in Table 8 which shows that the communication link for the LoRa radio module has a positive bit energy to noise density ratio () when using both long range settings in the RadioHead library. To maintain a reliable communications link, an ratio above 10 should be maintained which is achieved by setting the transmit power to 15dBm or above for both RadioHead long range settings.

### **Discussion**

The investigation to determine if the number of packets dropped can be reduced could not provide a set of radio parameters or test conditions that produce consistent results. The testing showed that only a portion of the packets not been received are rejected by the LoRa module (payload or header CRC check errors, checksum errors, bad lengths, etc.) with the rest not being received by the LoRa module at all (not detecting the preamble). At the conclusion of the testing, further investigation into the settings for the LoRa radio module was conducted to allow for the data that is received by the module to be passed to the Arduino for processing regardless of any errors present which found that the proprietary nature of the CRC method used by SEMTECH prevented any modification of the receive process.

The number of packets dropped by the LoRa module throughout the whole testing process was determined to be less than 1% of number of packets transmitted. To prevent the loss of all the data at the receiving station, is was decided that the transmitted identification and telemetry data will be separated as opposed to providing all the information in the one radio packet. The identification of each satellite was determined to be 4 hexadecimal characters (2 Bytes of data) which allows for a total of 65,536 combinations of satellite addresses with each identification radio packet containing 2 sets of satellite identification codes for a total of 4 Bytes of data. During each transmit phase of the radio beacon, the identification packet will be repeated 4 times followed by one packet of 50 Bytes containing the telemetry data. This transmission format was selected due to the inability of preventing radio packets from being dropped by the LoRa receiver. If a radio packet is missed, then the chances that the identification data is not collected is extremely small well as allowing multiple transmissions provide alternate signals to track if one is missed.

The investigation for the LoRa radio settings using the LoRa calculator suggests that the RadioHead (2) default settings is a better solution for this project when compared against the (3) settings. The results from the testing showed that the (2) default settings was able to sustain a reliable communications link for a larger FSPL loss showing that it can operate a link for a longer distance (the difference depends on the transmit power). The testing also revealed that a LoRa module with the (2) default settings has less Time-On-Air, occupies a smaller bandwidth on the radio spectrum and has a higher Bit energy. These factors contribute to the decision that the (2) default settings for the radio will be used for all further testing while the transmit power will by the calculation of the communications link budget.

The calculations for the link budget for this communications link show that there is a significant increase in the when using the long range settings from the RadioHead library with the (2) settings providing a higher ratio than the (3) settings. The (2) settings utilizes a smaller bandwidth (31.5kHz) as opposed to the (3) settings (125kHz) which results in the (2) settings having an approximate 20% higher energy per bit value as opposed to the (3) settings. These factors determine that the (2) long range LoRa setting available in the RadioHead library will be selected for this further testing of this application.

\*Talk about the govt regulations and how they affect the final TX power settings\*

### **Summary**

The testing carried out on the communications link has determined that the RFM96 LoRa radio module operating at 437MHz can operate a reliable data link between a satellite radio beacon in LEO and a ground receiving station. The communication requires that RFM96 LoRa module use the default (2) settings in the RadioHead library with a transmit power of 15dBm to maintain a bit energy to noise density ratio above 10. The testing found that the packet error rate of the LoRa module required that separate packets of data be sent to include a redundancy to ensure the satellite information is received at the ground station for every transmit phase of the radio beacon software cycle.

## Ground Receiving Station

It has been shown that the communication link can support the reliable transfer of data between the satellite radio beacon and a ground receiving station which leads to the design of the ground receiving station. The major design constraint for the ground receiver is to produce a design using cost effective components that has an acceptable level of tolerance in determining the position of the satellite. The position of the satellite is determined using the time difference of arrival (TDOA) of the radio signal at multiple ground stations which requires an accurate and common timing source between the stations and an accurate method of measuring time.

### **Materials and Methods**

The first initial design decision was to utilize the Global Navigation Satellite System (GNSS) in the ground receiving station to provide the geo-spatial location of the ground station, the Coordinated Universal Time (UTC) for a common timing source and A pulse per Second (PPS) signal for synchronizing the processor timing. The initial design of the ground receiving station will include a global positioning development module based on the U-Blox NEO-7M GNSS module as it has a positional accuracy of 2.5m, a 30ns PPS signal accuracy available on an external pin and cost less than $20. The NEO-7M GNSS module was paired with a 28dB GPS Antenna for signal reception which cost less than $15.

The second initial design decision was to utilize the RFM96 LoRa module on the same breakout board as used in the satellite beacon prototype the radio communication. This allows the radio module to utilize the same software and libraries used in the beacon development to provide continuity between the two systems. The breakout board used in this design contains an SMA connector allowing for a simple 3.5dBi helix antenna or a 12dBi Dipole antenna to be used for testing with the total cost for the radio and antenna being approximately $22.

The last initial design decision was to select the computer processor that will be used to drive the LoRa and GNSS modules and can accurately measure time to a precision required for this application. The first decision to limit the solutions to an Arduino based Microcontroller was made to ensure a processor was selected that is well resourced, contains enough peripherals and is easy to use which reduces the available solutions to the Arduino Uno and the Arduino Due. The Uno was selected for the initial design as the cost was substantially less with it being noted that the Due processor speed (84MHz) is much higher than the Uno processor (16MHz) which could increase the precision of time measurement if it is required. The initial design of the ground receiving station is below shown in Figure 4 with the total cost of components for the ground receiving station being under $80.

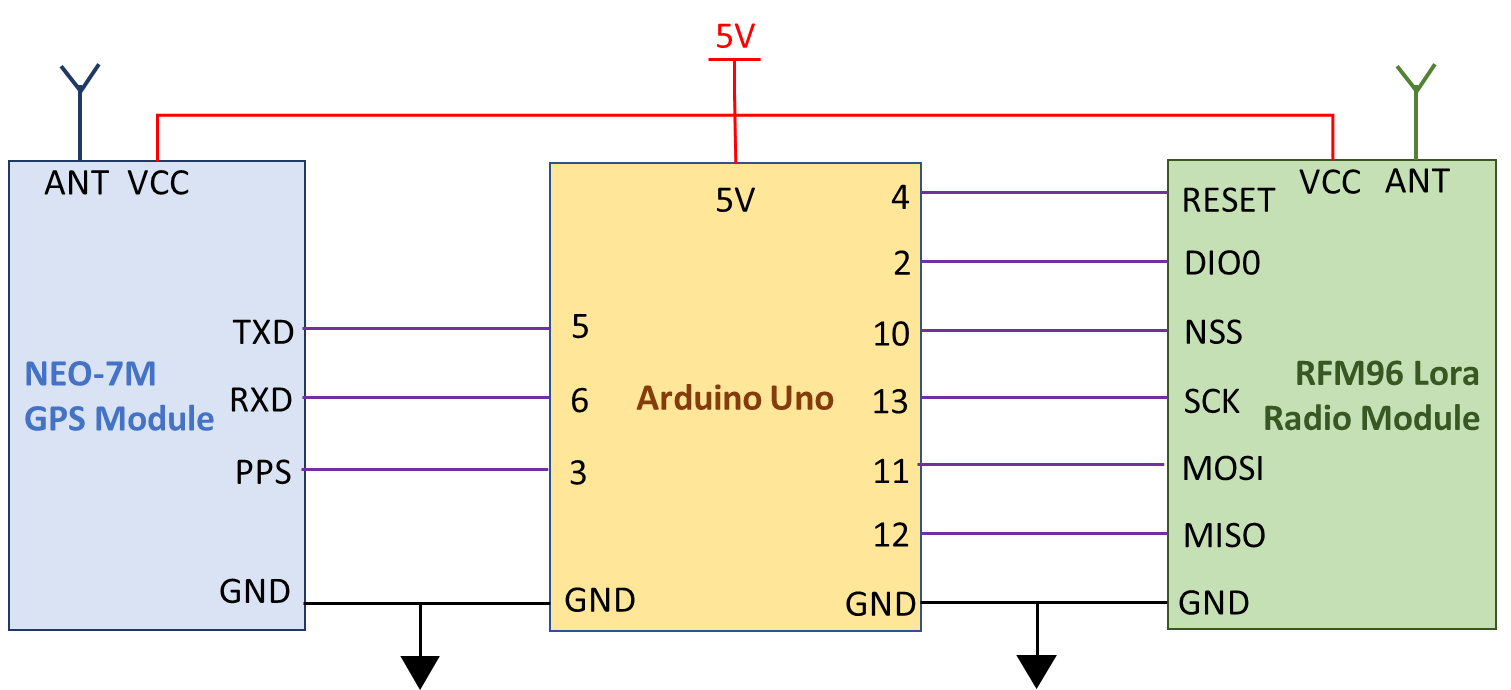


Figure 4 - Satellite ground receiving station design with connections

After the initial design decision were made, the next step was to develop the software code for the ground receiving station which is derived from the software flow chart detailed in Appendix G. The initial operation of the ground receiving station was planned such that as the ground station receives each packet (4 identification and 1 telemetry radio packet) it produces a time stamp that marks the time of arrival which is referenced against the arrival of the next PPS signal. The GPS data is then saved which contains the current UTC time to a second precision and positional data of the ground station. The timestamps, GNSS data (position and UTC), the identification data and the telemetry data are then passed on for further processing. The number of clock cycles between each packet time stamp and the PPS signal is used to determine the precise time of arrival of each radio packet with relation to the GNSS provided UTC. The measured time of arrival, synchronization of GNSS UTC and determined position of four ground receiving stations allows for the calculation of satellite position using a TDOA ranging technique.

The primary focus of testing the ground receiving station will be to determine the possible sources of error in the parameter that determine the tolerance of positional data. The initial research and testing of the system identified the following sources of error that could produce an error in the measurement of distance between the beacon and ground station…

### The resolution of the Arduino built-in timer function, micros()

1. The number of clock cycles taken to carry out an Interrupt Service Routine (ISR)
2. Oscillator frequency drift due to temperature, tolerances and other sources of error
3. Tolerance of the GNSS PPS signal – 30ns
4. Accuracy of the ground station GNSS position – between 2-10m
5. The time taken for the LoRa module built-in software to carry out integrity checks (time between when the signal is received and when it is made available by the LoRa module) – unknown
6. The resolution of the ATMEGA328P processor clock cycles

A detailed description on how each error in measurement was investigated and tested is presented in Appendix H.

\*describe how ground testing will be carried out for the final testing\*

### **Results**

The initial testing of the time measurement using the *micros()* function built-in to the Arduino IDE software reveled that the resolution of this measurement was found to be 4.096µs. The method in which the function is implemented by Arduino results in the output of the function being incremented only when the timer0 overflows causing the 4.096µs timing resolution which would equate to distance error of up to 1.23km.

The testing of using the ATMEGA328P processor Timer1 to count the number of cock cycle between events revealed errors in the difference in clock cycle counts between successive events timed at 1 second. The results showed that the difference in clock counts were less than 3 cycles for 97.3% of the measurements, with the statistics showing an absolute difference mean of 2.24, a median of 1 and a standard deviation of 10.63.

\*Need to talk about the Jitter\*

The investigation into how the ISR were carried out revealed that the method for entering the routine for counting clock cycles (Timer1 ISR, TIMER1\_COMPA\_vect) and measuring the GNSS PPS pulse (External interrupt ISR, INT1\_vect) are exactly the same and uses the same amount of clock cycles. The method of using ISR routines is common between each ground station and does not affect the difference in time for the TDOA calculation.

The tolerances for the errors in the GNSS PPS signal (30ns) and the GNSS positional measurement of the ground station location (10m) were found to be acceptable and no further testing was carried out for these errors.

The testing of the time difference in processing of two LoRa modules shows that the absolute time difference has a mean of 2.2901µs, a standard deviation of 1.6042µs, a median of 1.925µs and a maximum difference of 5.68µs.

### **Discussion**

The initial method of measuring time using the *micros()* function built into the Arduino IDE found that the resolution of the timer (4.096µs) resulted in an error equating to 1.23km when calculating distance, which is too large a tolerance for this application. This prompted an investigation into a method that would reduce the size of error which was to utilize the counter of the Timer1 clock cycles in the ATMEGA328P processor which has a resolution of 62.5ns. The testing carried out determined that there was a tolerance of 3 clock cycles (with 97% confidence) when using the clock counting method which equates to an error of 56.5m when calculating distance. The tolerance of the GNSS PPS signal is 30ns (distance measurement error of 9m) and the tolerance of the GNSS position is 10m which results in a total distance error of 19ms for the GNSS modules. The largest source of error is from the difference in time it takes for each LoRa module to process the same received radio packet. The tolerance in processing time was determined to be 5µs (with 92.6% confidence) which equates to an error in distance calculation of 1.5km.

The inclusion of all sources of error in calculating the distance from the beacon to a single ground station results in a possible error of 75.5m and if four ground stations are used in the TDOA calculation then this increases to 302m. When the time difference of processing is included in the distance calculation then this results in a total possible error of 1.8kms possible when determining the position of the satellite.

* Talk about error if LoRa processing can be improved using CAD signal and not RX signal
* Compare above against final testing
* **Talk about how software is implemented, and the collected data is sent from Arduino to matlab or a third-party program**

### **Summary**

* Determine final tolerance in measuring and how it will be implemented with TDOA

# 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.

# 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.

# Acknowledgements

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