1) Good morning/afternoon, my name is Pilot Officer McKee and I am to present my thesis project

The design of a small satellite UHF radio beacon for identification, telemetry, tracking and control.

2) It is estimated up to 2400 satellites will launch into Low Earth Orbit over the next 5 years.

This is a result of a significant decrease in cost to design, manufacture and launch a small satellite

A considerable amount of satellites are launched into the LEO environment by organizations with little to no space experience

This has resulted in a mission failure rate of 55% for academic institutions and 23% for commercial enterprises.

3) These two conditions have led to an increase in satellites and space debris in the LEO environment producing additional challenges for space monitoring and operations

Research has identified three problems to be addressed:

1. The increased demand on expensive space monitoring equipment to maintain Space Situational Awareness
2. The large failure rate of small satellites leading to an increase in space debris
3. The increased difficulties in identifying small objects in the LEO environment

4) To address the identified problems, the design of a satellite UHF radio beacon system is proposed to provide:

1. A better technique of uniquely identifying an object in LEO
2. A cost-effective system that can track active, End of Life and failed satellites
3. A method of obtaining satellite telemetry or health data irrespective of a failure in any other satellite system
4. An alternative communications pathway for satellite control

5) The Satellite UHF radio beacon system will be separated into 3 components:

1. **The satellite radio beacon** – That is a self-sustained UHF communication system that can operate independently of all other satellite systems
2. **The communications link** – which supports the transmission of data for a slant range of 2000km
3. **The ground receiving station** – which can capture the transmitted data, record the RF signals time of arrival and pass this data to a peripheral device for processing.

6) The satellite beacon can be linked with other satellite systems to collect telemetry data and contains a unique 16-Bit address

This information is placed into data packets and periodically transmitted from the beacon’s UHF radio

This is followed by a short period of time where command data can be received by the radio.

The data transmitted from the beacon is collected at multiple graphically dispersed ground stations with a timestamp of the signals precise time of arrival.

This data is then passed to a peripheral device where the satellites estimated position can be calculated using the time difference of arrival between three ground stations

7) The satellite UHF radio beacon must be self-sustaining and independent of all other satellite systems

To achieve these aims the beacon must contain its own:

* **Processor** – that is based on the Arduino Pro Mini (APM) module containing an ATMEGA328 processor
* **Radio Transceiver** – which is a RFM96 LoRa radio module, that uses an ultra-long range spread spectrum communication technique
* **Power Generation, Storage and Regulation** – which contains silicon solar panels, a super-capacitor storage system and a buck converter for power regulation

8) The software cycle for the radio beacon was developed to comply with the following requirements:

* The beacon is required to maintain 30 minutes of radio silence after release from the launch vehicle
* The radio must have a period in which it can receive a command to cease transmissions
* The power down period of the software cycle must be varied to prevent synchronisation of transmissions

The beacon software operates by powering down the radio and processor for 30 minutes after initialisation

The software then runs through a periodic cycle where:

* The telemetry data is collected
* And packaged with the satellite identification and transmitted
* The radio is then placed into receive mode for 1 minute
* And finally, the processor and radio are powered down for between 4 to 6 minutes

9) The aim of the satellite beacon design is to minimise Size, Weight and Power (SWaP) of the system, with reducing the current consumption of each component being the focus of testing.

**The testing found the following methods to reduce the beacon current consumption:**

1. Placing the LoRa module into sleep mode where possible
2. Placing the processor into low power mode when practical
3. Minimizing the *receive* and *transmit* phase in the beacon software cycle
4. Reducing the TX power and data packet size to as small as possible

**Some additional observations were made during the testing:**

* One solar panel could not support the beacon operation when the TX power is greater than 10dBm without a supplementary power source. The addition of the super-capacitor energy storage allows the beacon to operate up to the maximum TX power, 23dBm.
* The super-capacitors introduce an 8-and-a-half-minute delay to the system initialisation which can be factored into the launch phase of the software cycle
* Several radio packets were observed to be dropped by the LoRa module which was investigated during the comms link testing

10) The ground testing has shown that the operation of satellite UHF radio beacon can be self-sustained using a single silicon solar panel and the super-capacitor energy storage system

The energy stored in the super-capacitors can provide 74 minutes of beacon operation when no power is being generated

There is a combination of analogue, digital and serial connections remaining to collect telemetry data from other satellite systems with 50% of the system memory remaining to develop the other software functions

An Investigation into selecting space-ready components and creating a PCB design is required before mission-readiness testing can be commenced

11) The parameters for the communications link testing are based upon a satellite in a sun-synchronous LEO orbit with a 600kms height and 98° inclination.

This results in a maximum slant range of 2000km or a 151.3dB Free-Space Path loss

12) The first investigation carried out was to determine why the LoRa radio module was dropping the received data packets.

The reason for dropped packets could not be determined because of the proprietary nature of the LoRa software and no methods could be found to bypass the software receive process.

The packet error rate found during the testing resulted in changing how the data is transmitted with the identification data being repeated in 4 sequential radio packets followed by a separate telemetry data packet.

This method of transmission significantly reduces the probability of not receiving the satellite unique identification

13) The comms data link was verified for a 2000km range with the results used to determine the LoRa radio software settings and TX power

The first step was to estimate the LoRa receiver sensitivity using the manufacturers calculator tool

The next step was to calculate the communications link budget using various TX Power levels

And the final step was to verify the calculated results with the ground-based testing

The LoRa radio software settings was obtained from the default settings of the open-sourced RadioHead packet radio library

14) The simplified equations and assumptions used for the link budget calculation are presented on the slide and were used for the 0, 2 and 3 default radio settings with various TX powers.

A TX power of 15dbm results in a received Eb/N0 greater than 10 when the 2 or 3 default radio settings are used, with the 2 default settings having slightly better results

15) The ground-based testing was carried out by connecting two LoRa modules with coaxial cables and varying attenuation to determine the maximum FSPL and calculated range for which the receiver collects consistent data.

The results of the ground testing are congruent with the LoRa calculator estimates and link budget calculations

The RadioHead (2) default settings with a TX power of 15dBm was selected for the LoRa radio module to balance the satellite beacon power requirements, received Eb/N0 and data rate.

Using these settings result in an Eb/No of 14.38 which allows a safety margin for unaccounted losses

16) The ground receiving station must be able to capture the transmitted data, record the precise time of arrival of the RF signals, determine its global location and pass data to a peripheral device.

To achieve these aims the ground receiving station contains:

* **Processor module –** using an Arduino Uno board
* **Radio transceiver –** which is the RFM96 LoRa radio module
* **GPS Module –** that is a U-Blox GNSS module with a Pulse-per-Second signal

17) The ground receiving station software cycle operates by:

* Capturing the data from each received packet and timestamping the number of processor clock cycles that have occurred (with the 1st signal resetting the clock cycle count to zero)
* After the telemetry data is received, the GNSS data is captured and timestamped at the next GNSS PPS pulse
* The number of clock cycles between the next 3 PPS signals are collected and averaged to determine the true oscillator frequency and calculate the clock cycle length
* The collected data is then passed to a peripheral device which uses the calculated clock cycle length and signal timestamps to determine the time of arrival of each signal referenced to the captured UTC

18) The first investigation was to test and quantify the identified sources of uncertainty in measuring time or distance which were found in:

* The Arduino timing function resolution, which led to using the clock counting technique
* The Timer1 processor clock counting technique itself
* Initiating the Interrupt Service Routine process
* The Oscillator drift and tolerances
* The GNSS PPS and position tolerance
* And, the difference in LoRa processing time

The total estimated uncertainty in the time difference of arrival between two ground stations is 5.25µs, which equates to an error of 1.58km when estimating the position using the TDOA calculation technique.

19) For the verification testing, a single transmitted signal was received by 2 ground stations at the exact same time with the measured time difference in arrival representing the total uncertainty of the time measuring technique

The results show a total measured uncertainty of 1.7ms which equates to a positional calculation error of 510km which is much larger than the tested uncertainty of 1.58km

The considerable increase in uncertainty is most likely caused by the implementation of the processor clock counting ISR

The clock counting technique requires examination, with a focus on timer capture mode before a reliable TDOA algorithm can be used to estimate the satellites position.

20) The aim of this project was to produce an initial prototype design for a self-contained and independent radio beacon that can transmit data from a small satellite in low earth orbit.

The project was extended to include a prototype design for a ground receiving station with a tracking function.

The satellite radio beacon system has been tested and verified to be capable of

* Sustaining beacon operation without any input
* Operating for a 2000km range
* Transmitting the satellite identification from the beacon to a ground station
* Transmitting satellite telemetry and health data from the beacon to a ground station
* Executing a satellite control command from a ground station
* Measuring a signals Time of Arrival with a 1.7ms tolerance

The initial design for the small satellite UHF radio beacon system has proven the concept for the Identification, Telemetry and Control function which addresses the problems of

* Uniquely identifying a satellite
* Reducing the failure rate by identifying cause of failure
* Reducing space debris by providing a command pathway for on-orbit correction

Further investigation is required to obtain a reliable and accurate tracking function that address the reliance on costly space monitoring equipment.

21) Further investigation is required to reduce the uncertainty of time measurement, with a focus on the processor *Timer1* clock counting implementation in the ground station software

If the uncertainty of time measurement is reduced, then the next step is to:

* Implement a TDOA algorithm that calculates estimated position based on Lat/Long position
* Develop a user interface program for the ground receiving station
* Develop a server system for the collection and processing of ground station data
* Produce a satellite radio beacon design ready for space mission readiness testing