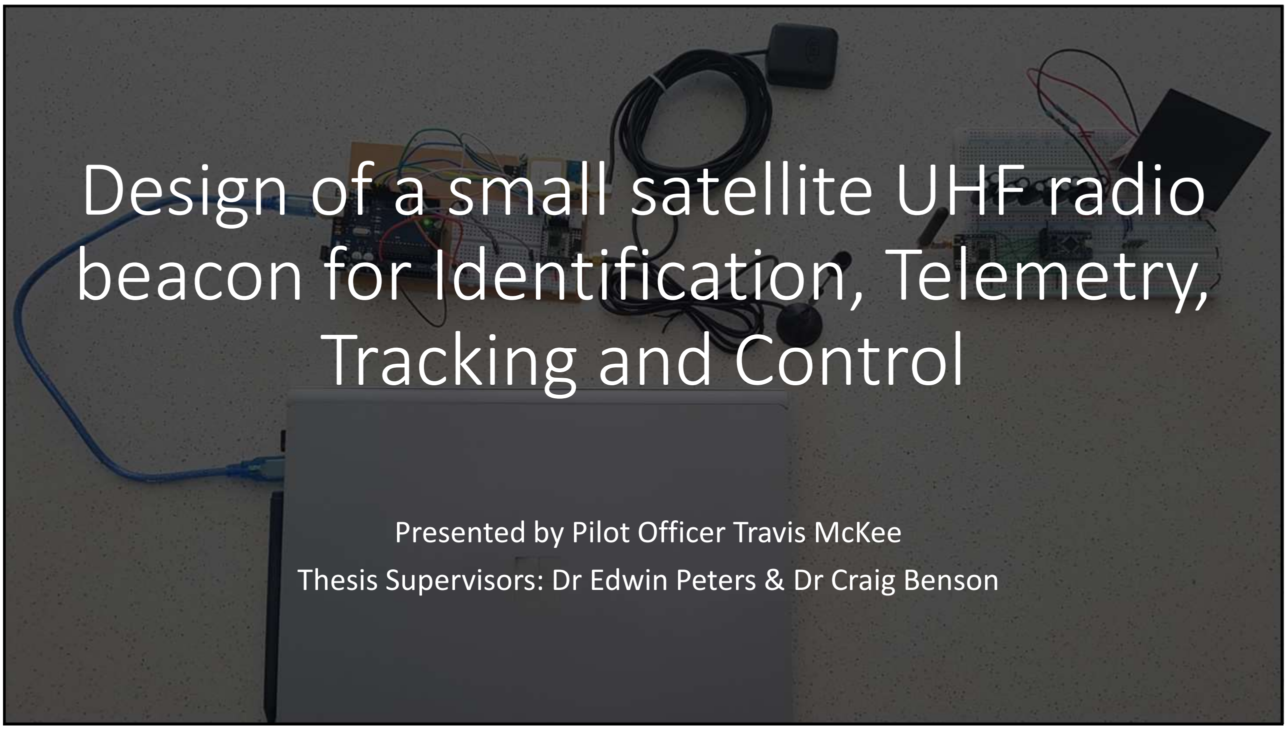
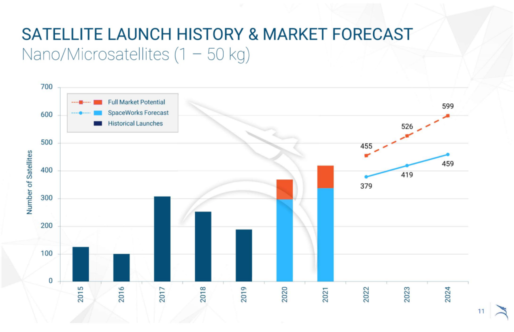


Design of a small satellite UHF radio beacon for Identification, Telemetry, Tracking and Control

Presented by Pilot Officer Travis McKee
Thesis Supervisors: Dr Edwin Peters & Dr Craig Benson

1

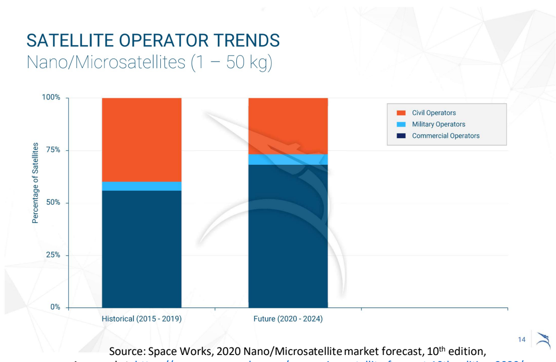
Introduction



Source: Space Works, 2020 Nano/Microsatellite market forecast, 10th edition, Accessed at: https://www.spaceworks.aero/nano-microsatellite-forecast-10th-edition-2020/

"SpaceWorks estimates 1,800 – 2,400 nano/microsatellites will require launch over the next 5 years"
2020 Nano/Microsatellites market forecast, 10th Edition

"mission success rates average 45 percent and 77 percent between academia and industry, respectively"
U.S. Space program Mission Assurance Improvement Workshop



Source: Space Works, 2020 Nano/Microsatellite market forecast, 10th edition, Accessed at: https://www.spaceworks.aero/nano-microsatellite-forecast-10th-edition-2020/

2

Introduction

Additional challenges for monitoring and operating in the Low Earth Orbit (LEO) environment:

1. Increased demand on resource expensive space monitoring equipment to maintain Space situational awareness (SSA)

2. An increase in space debris due to a large failure rate of small satellites

3. Difficulties in identifying small objects in the LEO environment

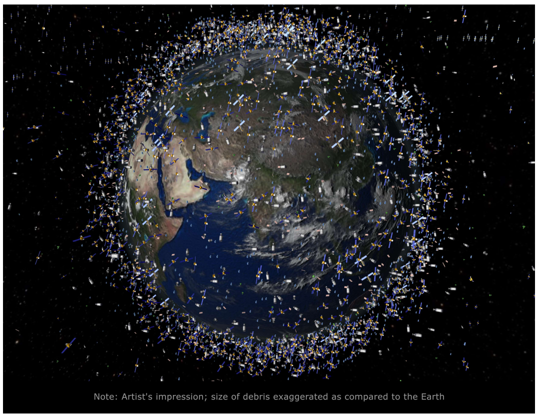


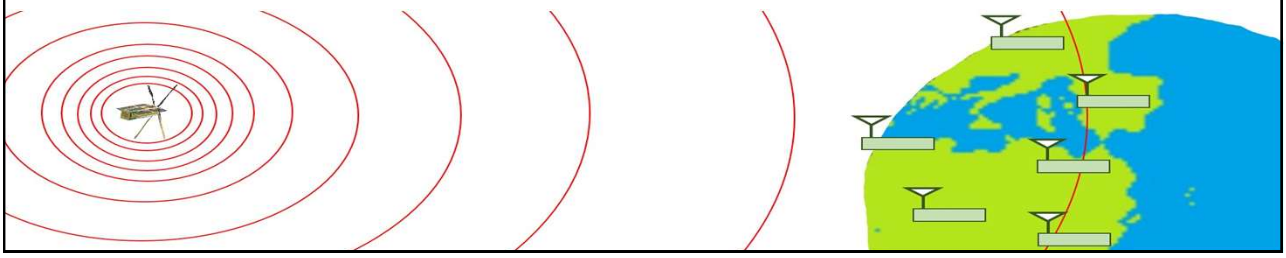
Image source: Universe Today, Space and astronomy news
Accessed at: https://www.universetoday.com/85322/what-is-low-earth-orbit/

3

Introduction

The purpose of this project is to design a satellite UHF radio beacon system which provides:

1. A better technique of uniquely identifying an object in LEO
2. A cost-effective system of tracking objects
3. A method of obtaining satellite telemetry data irrespective of a failure in any other system
4. An alternative communications pathway for satellite control



4

Theory of Operation

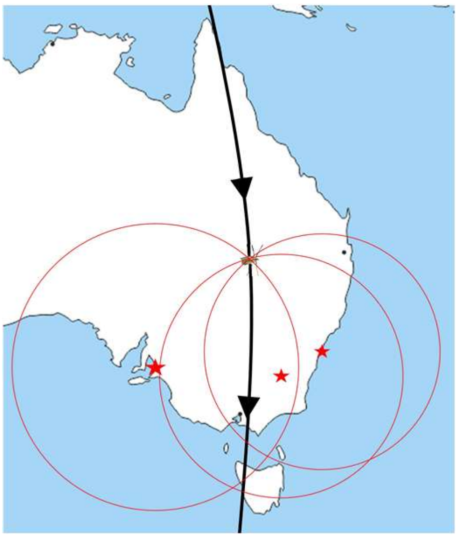
The Satellite UHF radio beacon system will be separated into 3 components:

- **The satellite radio beacon** – A self-sustained system that can operate independently of all other satellite systems
- **The communications link** – Supports the transmission of data from the radio beacon in LEO to a ground receiving station (2000km slant range)
- **The ground receiving station** – Captures the transmitted data, records the precise time of arrival (TOA) and passes data to a peripheral device.

1. Satellite radio beacon 2. Communications link 3. Ground receive station

5

Theory of operation



- The satellite beacon periodically transmits the collected telemetry data and a unique address from the UHF radio
- Followed by a period where command data can be received
- The transmitted data is collected with the measured time of arrival at multiple graphically dispersed ground stations
- The collected data and timestamps are passed along to a peripheral device for processing.
- The time difference of arrival (TDOA) between the three ground stations allows for the calculation of the satellites estimated position

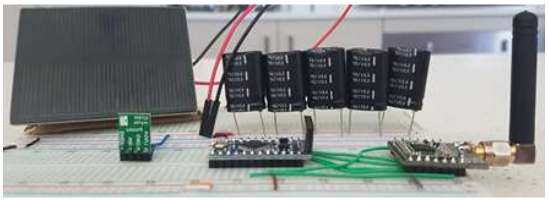
6

Satellite Radio Beacon

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

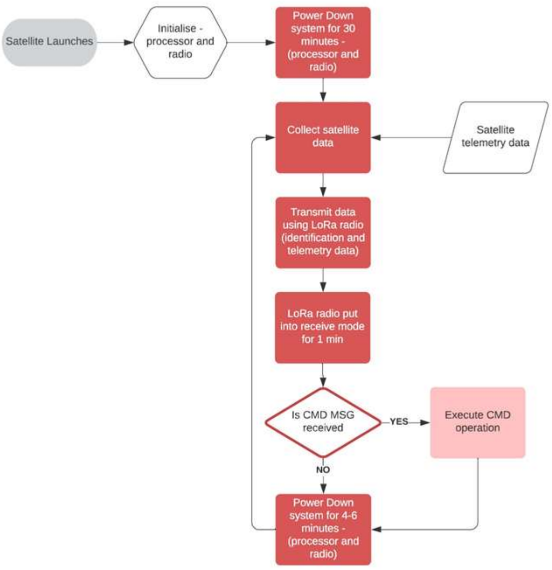
To achieve these aims the beacon contains its own:

- **Processor** –Arduino Pro Mini (APM) module containing an ATMEGA328 processor
- **Radio Transceiver** –RFM96 LoRa radio module, which uses an ultra-long range spread spectrum communication techniques
- **Power Generation, Storage and Regulation** – 0.5W Silicon solar panel, super-capacitor storage system and a buck converter regulator



7

Satellite Radio Beacon



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

- Maintain radio silence 30 minutes after release from the launch vehicle
- A receive period to receive a command to cease radio transmissions as required by ACMA and ITU
- A variable period for the power down phase to prevent transmission synchronisation

8

Satellite Radio Beacon

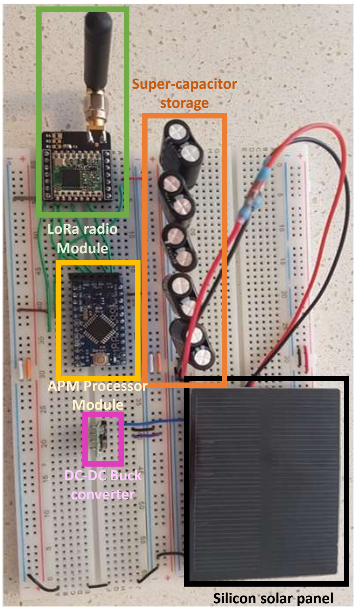
Manufacture of the satellite radio beacon prototype (see right) was a result of the testing carried out to minimise the Size, Weight and Power (SWaP) of each component

Methods to reduce the beacon current consumption:

- Placing the LoRa module into sleep mode
- Placing the processor into low power mode
- Minimizing the *receive* and *transmit* phase
- Decreasing the TX power and data packet size

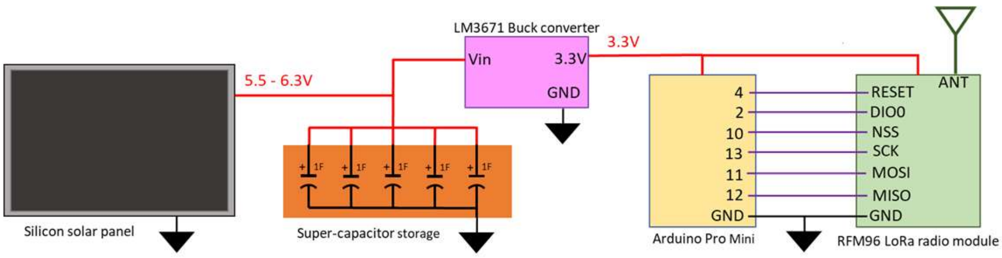
Additional observations during the testing:

- One solar panel could not support beacon operation without supplementary power
- The super-capacitors introduce an 8 and ½ min delay to initialisation
- Several radio packets were dropped by the LoRa radio module (investigated in the communications link testing)



9

Satellite Radio Beacon



<u>Satellite UHF radio beacon conclusion</u>

- A single solar panel can sustain beacon operation when using the super-capacitor storage
- The power storage system provides 74 minutes of operation when no power is being generated
- A combination of connections remaining to collect satellite telemetry data
- Over 50% of the system memory remains for additional software development

Investigation of space-ready components and a PCB design is required before mission-readiness testing can be commenced

10

Communications Link

The parameters for the communication link testing are based on a sun-synchronous LEO orbit with an orbital height of 600km and a 98° inclination.

Resultant Orbital characteristics:

- 90-minute orbital period
- ~9-minute view window
- 2000km maximum slant range
- 151.3dB Free Space Path Loss (at 2000km)

11

Communications Link

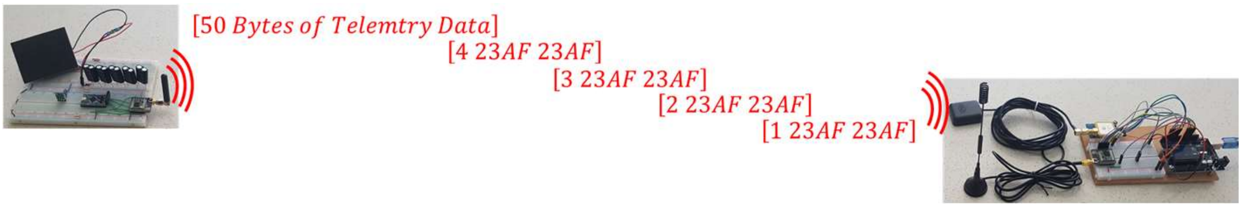
First investigation
Determine why the LoRa radio module was dropping received packets

Result

- The reason could not be determined due to proprietary nature of the LoRa module software
- No methods could be found to bypass the LoRa software receive process
- Analysing over 1 million Bytes of data found a Packet Error Rate (PER) of ~1%

Mitigation

- The PER changed how the identification and address data was transmitted
- Separating the data packets results in a 0.00001% probability of not receiving the identification data



12

Communications Link

Second investigation

Verify the UHF communications link for a 2000km slant range (151.3dB FSPL) and determine the LoRa radio software settings and TX power.

Testing procedure

1. Receiver sensitivity estimated using the LoRa modem calculator tool (available from Semtech)
2. The link budget was calculated for various TX power (5, 10, 15 and 20dBm)
3. The results were verified with the ground-based testing

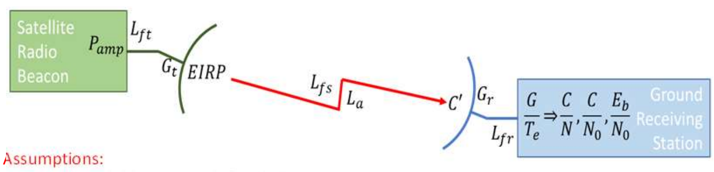
The radio settings used for testing were from the open-sourced RadioHead library default settings

RadioHead default setting	LoRa module radio configuration	Bandwidth	Coding rate	Spreading factor	Preamble length	Estimated Bit rate	Estimated receiver sensitivity
(0)	Medium range & data rate	125 kHz	4/5	7 (128 chips/symbol)	12	5469 bps	-124 dBm
(2)	Long range, slow data rate	31.25 kHz	4/8	10 (512 chips/symbol)	12	152.59 bps	-139.4 dBm
(3)	Long range, slow data rate	125 kHz	4/8	12 (4096 chips/symbol)	12	183.11 bps	-138 dBm

13

Communications Link

Link Budget Calculations



$$C' = P_{amp} - L_{ft} + G_t - L_{FS} - L_A$$

$$\frac{C}{N_0} = C' - 10.\log(k) + \frac{G}{Te} - L_{fr}$$

$$\frac{E_b}{N_0} = \frac{C}{N_0} - 10.\log(f_b)$$

Assumptions:

- LoRa module has a 0.5dB feeder loss
- 290k ground temperature
- 3.5dBi helix transmitter antenna
- 3.5dBi helix receiver antenna (noting there is a 12dBi antenna that could be used)
- Maximum bit rate (f_b) obtained using the LoRa modem calculator tool (proven using hand calculations)

Calculated values for the communications link budget

Link Budget calculations for the satellite radio beacon communications link at 2000kms												
RadioHead default settings	(0) Medium Range Settings				(2) Long Range Settings				(3) Long Range Settings			
Parameter	Downlink				Downlink				Downlink			
Transmitter Power, Pamp (dBm)	5	10	15	20	5	10	15	20	5	10	15	20
Bit Enegy/Noise Density Ratio, Eb/No	-8.73	-3.73	1.27	6.27	4.38	9.38	14.38	20.38	3.59	8.59	13.59	18.59

14

Communications Link

Ground-Based Testing

Two LoRa modules were connected with coaxial cables and attenuation that represents the maximum FSPL (and calculated range) for the consistent reception of data packets

Results of the ground-based communication link testing

Largest measured FSPL attenuation and distance for consistent data reception									
	Transmit power (dBm)	5		10		15		20	
RadioHead default setting	Reciever sensitivity (dB)	Total attenuation (dB)	Distance (kms)	Total attenuation (dB)	Distance (kms)	Total attenuation (dB)	Distance (kms)	Total attenuation (dB)	Distance (kms)
(0)	-124	131.14	195	137.14	390	141.14	620	145.14	980
(2)	-139.2	146.14	1100	151.14	1950	155.14	3100	161.14	6200
(3)	-138	144.14	880	150.14	1750	155.14	3100	160.14	5500

Communications link conclusion

The RadioHead (2) default setting with a 15dBm TX power was selected for the LoRa radio module

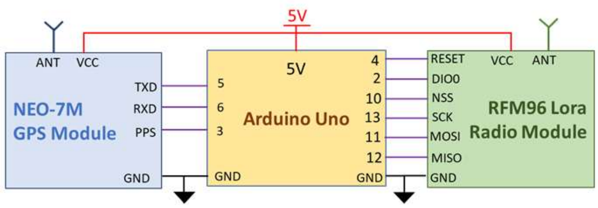
These settings balance the satellite beacon power consumption, received E_b/N_0 (14.38) and data rate

Ground Receiving Station

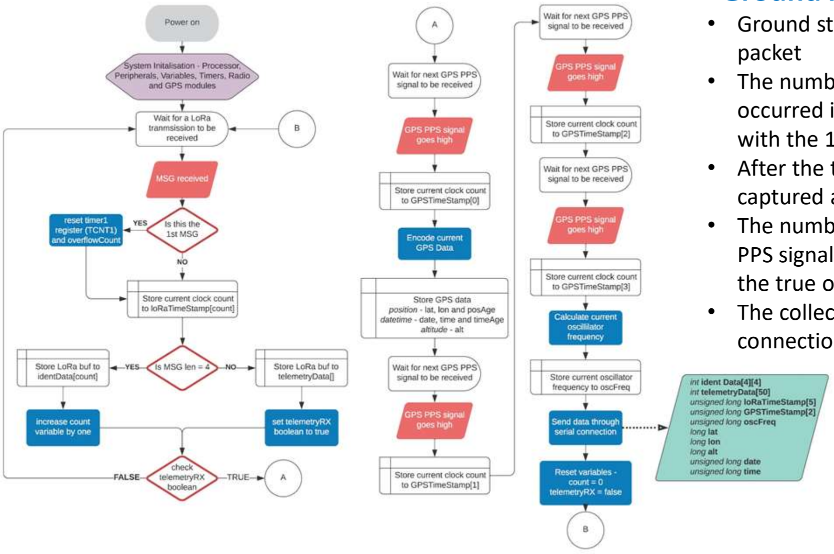
The ground receiving station must be able to capture the transmitted data, record the precise time of arrival of the RF signals, determine its global location and pass data to a peripheral device.

To achieve these aims the ground receiving station contains:

- **Processor module –** Arduino Uno development board with an ATMEGA328P processor and 16MHz oscillator
- **Radio Module –** RFM96 LoRa radio module
- **GPS Module –** U-Blox NEO-7M GNSS module with a Pulse-per-Second signal synchronized to Coordinated Universal Time (UTC)



Ground receiving station



Ground receiving station software cycle

- Ground station captures the data from each received packet
- The number of processor clock cycles that have occurred is timestamped (the clock count is reset with the 1st Received signal)
- After the telemetry data is received, the GNSS data is captured and timestamped at the next PPS pulse,
- The number of clock cycles between the next 3 GNSS PPS signals are collected and averaged to determine the true oscillator frequency
- The collected data is passed through the serial connection to a peripheral device
    - The true oscillator frequency is used to determine the length of the processors clock cycle
    - This value is used to calculate the time of arrival of each timestamp with reference to the captured UTC

17

Ground receiving station

First Investigation

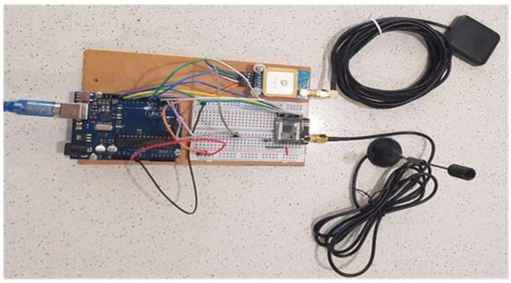
To test and quantify the identified sources of uncertainty in measuring time/distance:

1. 4µs Resolution of the Arduino timing function, *micros()* – led to using the clock counting technique
2. Error in *TIMER1* processor clock counting technique, ±3 clock cycles ~187.5ns (equates to 56.5m)
3. Number of clock cycles taken for an Interrupt Service Routine (ISR), no error time difference
4. External oscillator drift and tolerances, < 2fs (negligible)
5. GNSS PPS signal tolerance, 30ns (9m)
6. GNSS position tolerance, 10m
7. Difference in LoRa software receive processing time, 5µs (1.5km)

Results

The total estimated uncertainty in the time difference of arrival between two ground stations was 5.25µs.

This equates to an uncertainty of 1.58km when estimating the position using the TDOA calculation technique.

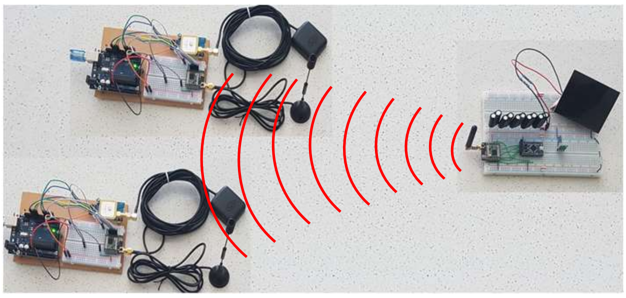


18

Ground receiving station

Final verification Testing
Two ground stations were uniformly connected to a single radio beacon
The measured time difference of arrival is the level of uncertainty in measuring time

Results
Total measured uncertainty was 1.7ms, which equates to TDOA distance calculation error is 510km



Ground Receiving station conclusion

The estimated uncertainty in satellite position was 1.58km, the verification test revealed an uncertainty of 510km

The mostly likely cause of the large uncertainty is 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.

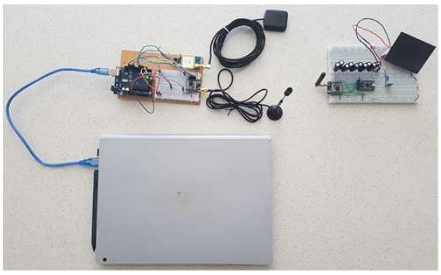
19

Conclusion

Project aim: Prototype design for a self-contained and independent radio beacon
Project extension: Prototype design for a ground receiving station

The Satellite UHF radio beacon system has been tested and verified to:

- Sustain beacon operation without any input
- Operate for a 2000km range
- Transmit the satellite identification to the ground station
- Transmit satellite telemetry and health data
- Execute a satellite control command from a ground station
- Measure a signal Time of Arrival with a 1.7ms tolerance (510km position calculation uncertainty)



➢ **The initial design for the small satellite UHF radio beacon system has proven the concept for the small satellite beacon Identification, Telemetry and Control**

➢ **Further investigation is required to obtain a reliable and accurate tracking function**

20

Recommendations

Further investigation is required to reduce the uncertainty of time measurement, with a focus 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

21