# Final report

## Design of New Generation eSAT Low SWaP, Robust, Two-Way, Low Latency, Narrow-Band, Ubiquitous Communications Product

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# Abstract

Adoption of digital tools and remote monitoring technologies by red meat producers requires access to cost effective connectivity in regional and remote locations. Increasing availability of satellite enabled connectivity across Australia is making it more cost effective for producers to have broadband internet connectivity at select key locations on farm (e.g. homestead, yards, vehicles etc.).

However, cost effective universal connectivity for narrowband Internet of Things (IoT) sensors and devices (e.g. Smart Tags, on-farm sensors etc.) remains challenging. The relatively high per sensor connectivity costs of available satellite solutions has contributed to the limited deployment of satellite enabled IoT devices at scale whilst commercially available cellular networks often lack the coverage required. To cover connectivity gaps some farmers are adopting hybrid mixed technology solutions and often establishing private terrestrial networks, which are suitable for many situations. However, they require new farm infrastructure such as towers and have limited range resulting in variable connectivity dependent on location and terrain and making them largely impractical for full farm IoT coverage over large operations.

To address the IoT connectivity gap, this project developed and demonstrated a Proof of Concept (PoC) low-cost direct to satellite communications system well suited to integration into livestock ear tags (and other IoT devices) through enabling highly efficient direct communication between IoT devices and existing Geosynchronous Earth Orbit (GEO) satellites. Traditionally, geostationary satellites have high latency and are relatively expensive, limiting their application for large scale deployment of real-time IoT devices to highest value use cases. However, the next generation GEO satellite communications module developed and tested in this project offers a new lowest-SWaP (Size, Weight, and Power), robust, two-way, low latency, narrow-band, communications product with a broad range of applications, including livestock tracking throughout Australia at a significantly lower total cost of ownership of monitoring and data collection devices than previously available.

# Executive summary


**Background**

Australian red meat producers stand to gain significant benefits from the adoption of Ag Tech and digital tools, including improved livestock management, enhanced productivity, and greater sustainability. Innovations such as individual animal GPS smart tags, remote monitoring, automated weighing systems, and real-time data analytics can transform operations across vast and often isolated properties. However, to fully realise these advantages, reliable and cost-effective IoT connectivity is essential. Without cost effective robust digital infrastructure, producers are unable to deploy and integrate these technologies at scale, limiting their ability to optimise performance, reduce costs, and meet evolving market and environmental demands.

eSAT Global offered an approach to the MLA Donor Company for low-cost data connectivity to every animal and every agricultural sensor throughout Australia. The cost of eSAT's connectivity solution is much lower than competing systems, thereby enabling higher Benefit-to-Cost Ratios (BCR) for producers.

eSAT's technology provides uniquely efficient two-way satellite connectivity. It does this by optimising the use of satellite resources for communication of small volumes of data (i.e., around 100 bits). eSAT enables ubiquitous connectivity with pricing of a few dollars per year per device. An example of eSAT's advantages is the satellite power needed to provide service: For the same service quality, eSAT uses over 1,000 times less power than its primary competitor, Non-Terrestrial Networks (NTN). This factor of 1,000 translates directly to much lower costs and to much higher data robustness.

This project has taken eSAT technology and applied it to Australian agricultural applications for red meat producers.

**Objectives**

The goal of this project was to (a) develop an eSAT satellite communication module, which will enable implementation of low-cost agricultural IoT devices, and (b) demonstrate the functionality and efficiency of the eSAT system.

## Methodology

Key steps have included:

- **System design**: Design and development of red meat industry applications using eSAT satellite technology
- **Device creation**: Satellite communications module and prototype device implementation
- **End-to-End Integration**: Connectivity from gateways through satellites to and from prototype devices, including testing at several global locations
- **Trials and report of key findings:** demonstration of connectivity to livestock tags and IoT devices (e.g. water/soil sensors) in Australia and lessons learned, recommendations.

## Results/key findings

eSAT successfully developed a low SWaP (Size, Weight and Power) satellite communications module and has undertaken demonstrations in prototype smart livestock tags, water level monitors and soil moisture monitors. Anticipated performance of the modules has been preliminarily verified in the field and a path for partnering with producers to scale up is now recommended.

## Benefits to industry

The report demonstrates that eSAT's ultra-low-cost, low-power satellite IoT system can deliver reliable, ubiquitous connectivity for livestock tags and on-farm sensors, dramatically lowering the cost of digital adoption. Access to affordable connectivity for IoT devices will become a key enabler for producers to unlock major productivity gains—from improved grazing management and animal welfare to reduced labour, better traceability, and higher overall profitability. Building on past modelling (Trotter et.al; 2018) it is proposed *"..the potential benefit of whole of herd/flock deployment as limited by likely adoption rates (and not including the costs of LBS systems) suggest total accumulated benefits of between $280 million (minimum) and $808 million (maximum) for the beef industry over a 10 year period. The accumulated benefits for sheep would be $204 million (minimum) to $501 million (maximum) over a 10 year period…"* Additional applications have the potential to reduce costs and improve efficiency of operations providing further benefits to red meat producers. An expected key benefit of increased digitisation will be an improvement in the efficient use of labour, reducing pressure on labour availability, in addition to likely productivity gains from more informed digital decision making.

## Future research and recommendations

Near-term steps centre on commercialisation. Livestock tracking is expected to be the initial application, followed by a range of IoT services (water monitoring, weather stations, automated weighing, etc.). As the technology evolves, cost reduction will be ongoing. Securing early adopters whose value chains are at scale will enable ongoing enhancements to the technology stack. AgTech providers (e.g., developing tags and sensors) and partners will validate the impact of improved, cost-effective connectivity.

# Table of contents

Abstract ..... 2
Executive summary ..... 3
1. Background ..... 7
1.1 Purpose ..... 7
1.2 Uniqueness of eSAT Technology ..... 7
1.3 Glossary ..... 9
2. Objectives ..... 11
3. Methodology ..... 12
3.1 Breakdown of Methodology ..... 12
3.1.1 eSAT Module development ..... 12
3.1.2 Tasman Board development ..... 13
3.1.3 Livestock Tags ..... 15
3.1.4 IoT Devices ..... 16
3.1.5 Smart Paddock livestock location visualisation ..... 17
3.1.6 International Testing ..... 19
3.1.7 Australian Testing ..... 20
3.1.8 Data Analysis ..... 21
3.2 Performance Evaluation ..... 24
4. Results ..... 27
4.1 Module development ..... 27
4.2 Tasman board development ..... 27
4.3 Livestock tag and IoT device development ..... 27
4.4 Trials and performance ..... 27
4.4.1 Australian trials ..... 27
4.4.2 Global experience ..... 28
4.5 Data Analysis and Interpretation ..... 29
4.5.1 Livestock Tracking Performance Expectations ..... 29
4.5.2 Link Budget with good pointing and minimal obstructions ..... 30
4.5.3 EERS Propagation Model ..... 31
4.5.4 Antenna Gain and Combined Distributions ..... 33
4.5.5 Observed Performance ..... 35
4.5.6 Extrapolation Across Australia ..... 37

4.5.7 Reference Oscillator Stability ........ 41

4.5.8 Energy Harvesting and Storage ........ 43

5. Conclusion ........ 46

5.1 Key Findings and Their Relevance to the Red Meat Industry ........ 47

5.2 Functionality and Robustness of Connectivity: ........ 47

5.3 eSAT Module Development and Maturity of Tags: ........ 48

5.4 Size, Weight, and Power (SWaP) of Tags: ........ 48

5.5 Price and Commercial Viability: ........ 48

5.6 Remaining Issues and Future Directions: ........ 48

5.7 Benefits to industry ........ 50

5.7.1 Improved Grazing Management and Pasture Utilisation: ........ 50

5.7.2 Enhanced Animal Health and Welfare: ........ 50

5.7.3 Increased Biosecurity and Traceability: ........ 50

5.7.4 Reduced Mustering and Labour Costs: ........ 51

5.7.5 Theft reduction ........ 51

5.7.6 Positive Impact on Breeding Efficiency and Reproductive Management: ........ 51

5.8 Quantifiable Benefits and Favourable Benefit-Cost Ratios (BCR): ........ 51

6. Future research and recommendations ........ 54

6.1 Commercialisation Strategy ........ 54

6.2 Broader Applications ........ 55

7. References ........ 57

8. Acknowledgements ........ 59

# 1. Background

## 1.1 Purpose

The eSAT Global project sought to address the significant challenges faced by the Australian red meat industry due to limited and expensive data connectivity for IoT applications, particularly in remote regions. Existing solutions like cellular networks suffer from inconsistent coverage. Private networks are costly and complex to establish. Traditional satellite services are expensive and inefficient for the small data packets typical of IoT applications. These connectivity constraints have hindered the economic viability of various transformative business cases, such as real-time livestock location, behaviour and state ("LBS") traceability, advanced water resource management, and enhanced biosecurity measures. By developing a low-cost, next-generation direct-to-satellite communication system, the project aimed to deliver a technology capable of fundamentally improving access to connectivity across Australia, enabling widespread implementation of Agricultural IoT solutions.

The research outcomes were intended to provide a viable and economically compelling two-way satellite IoT solution. The project successfully developed a custom eSAT Module, which was integrated into a printed circuit board and and demonstrated in smart tags and IoT devices.

eSAT technology is designed for minimal power consumption and frugal use of satellite resources, supporting a projected smart tag price (by the end of 2027) of $40 AUD for a GPS-enabled tag with satellite connectivity, and data connectivity as low as $4 AUD per device per year. This equates to a $15 Total Cost of Ownership (TCO) with a tag price of $40 amortised over the 5 years ($8 per year) and assuming an annual connectivity and platform price of $7 (NB it is expected that early units will have an initial commercial price of around $70 per unit as the technology is scaled from POC to full commercial production). It is expected that prices will continue to decrease into the future noting outcomes of this project have identified opportunities to further reduce the size and weight to less than 20 grams, which should be beneficial from a tag retention perspective and also lead to lower costs.

## 1.2 Uniqueness of eSAT Technology

The project's uniqueness lies in its focus on leveraging existing Geosynchronous Earth Orbit (GEO) Mobile Satellite Service (MSS) satellites, like Space42, Viasat, and Ligado for narrow-band IoT connectivity. This approach offers a distinct alternative to the prevailing trend of Low Earth Orbit (LEO) constellation development, promising ubiquitous, two-way, low-latency, narrow-band communication at an unprecedentedly low cost.

eSAT provides ubiquitous communication of modest volumes of data (perhaps around 1,000 bits per day in 10 messages) with the following characteristics:

1. Robust communication, i.e., providing high probability of delivery, say, greater than 95%
2. Low cost of devices and data connectivity, totalling ~$15/year/device
3. Low Size, Weight, and Power (SWaP) of terminal devices, (e.g., enabling attractively priced practical livestock tracking)
4. Two-way connectivity (preferred) to enable efficient acknowledgements, device configuration, polling of status, messaging (e.g., to/from farmers), and control (e.g., of irrigation)

5. Continuity of connectivity, say with maximum latency of a few seconds, to enable prompt delivery of alarm type traffic, (e.g., livestock outside a geo-fenced area)

eSAT meets these goals with, by far, the least cost in the industry while ensuring connectivity robustness. The factors underlying eSAT's advantages include:

- The communications system is designed for purpose, i.e., to optimally achieve the combination of goals stated above. The implications, in terms of efficiency, typically involve factors of 100's or more. These factors drive data cost.
    - eSAT concentrates on frugal use of valuable satellite resources (power and bandwidth). For example, comparing eSAT with a repurposed non-satellite design (i.e., Non-Terrestrial Networks, which is based on terrestrial NB-IoT), the satellite power usage is more than 1,000 times less for the same performance.
    - With such advantages, eSAT can also provide robustness that is impractical for competitors. For example, competitors often require users to point devices towards the satellite to establish connections, which is not practical for livestock tags and other non-stationary applications.
- The eSAtT design enables terminal transmit power as low as ~0.2 mW in line-of-sight (ideal) conditions. This results in economic implementation of low SWaP devices with robust connectivity.
- eSAT utilises existing geosynchronous L-band and S-band satellites, which have high antenna gains.
    - These satellites, which were originally built for higher throughput services, have low cost-per-bit.
    - By operating at L and S Band specific radio frequencies with short wavelengths, devices can utilise small antennas. Hence, the overall dimensions can be compact, measuring only a few centimetres.
    - The geosynchronous orbit of these satellites means connectivity is continuously available and the time to communicate a message (the latency) is typically less the 2 seconds. Satellites operating in other orbits can have latency in the range of minutes to many hours depending on the number of satellites in the constellation.
- eSAT uses 2-way connectivity. This is not unique to eSAT but does differentiate it from some competitors. 2-way connectivity enables:
    - Control of equipment, e.g., irrigation
    - Configuration of terminals, e.g., setting the reporting rate for tags
    - Controllable error rates in the communication of information. For example, by implementing retransmission protocols, messages sent with errors can be repeated. The resulting transmission success rate, e.g., a Message Success Rate, can be configured by adjusting the allowed number of repetitions.
    - Control of the transmit power of the terminals and the satellites, where this enables both increased capacity and reduced energy usage.
    - Terminal code updates, where improvements in the software in terminals can be made 'over the air'.

## 1.3 Glossary

| | |
|---|---|
| AGCH | Access Grant Channel |
| ARQ | Automatic Repeat Request |
| BCCH | Broadcast Control Channel |
| BSR | Burst Success Rate |
| CQ | Central Queensland |
| CQIRP | Central Queensland Innovation Research Precinct |
| CAI | Common Air Interface |
| CIA | Country Industries Australia |
| CDF | Cumulative (probability) Density Function |
| dB | Decibels |
| dBm | Decibels relative to 1 milliwatt |
| dBW | Decibels relative to 1 Watt |
| ESI | Earth Station Interface |
| EIRP | Effective Isotropic Radiated Power |
| Ebi/No | Energy per Information Bit to Noise Power Spectral Density Ratio |
| EERS | Extended Empirical Roadside (propagation model) |
| EERS-A | Extended Empirical Roadside Availability (model) |
| EERS-AT | Extended Empirical Roadside Availability for Tags (model) |
| G/T | Gain over Temperature |
| GEO | Geosynchronous Earth Orbit |
| GBCW | Global Broadcast Continuous Wave |
| GNSS | Global Navigation Satellite Systems |
| GPS | Global Positioning System |
| IoT | Internet of Things |
| LBS | (Livestock) Location, Behaviour and State |
| LEO | Low Earth Orbit |
| MLA | Meat and Livestock Australia |
| MSR | Message Success Rate |
| MSS | Mobile Satellite Service |
| NTN | Non-Terrestrial Networks |
| PCH | Paging Channel |
| PDF | Probability Density Function |
| SNR | Signal to Noise Ratio |
| SWaP | Size, Weight, and Power |
| TCXO | Temperature Controlled Crystal Oscillator |
| TD | Terminal Devices |
| UE | User Equipment |

*acronyms_v.1.005.xlsx*

# 2. Objectives

The project's goal has been to develop a low-cost next generation direct to satellite communications system that would fundamentally improve the affordability of IoT connectivity across Australia livestock sector.

The objectives included the development of:

- the eSAT Module, i.e., a hardware device that provides the eSAT functionality (modem, radio, processing, etc.),
- a smart livestock tag based on the eSAT Module to enable testing in trials, and
- IoT devices supporting two AgTech applications.

The cost targets included $40 AUD for a GPS enabled tag with satellite connectivity and data connectivity pricing as low as $4 AUD per device/year.

Trial plans included 20 livestock tags and 5 IoT devices.

# 3. Methodology

## 3.1 Breakdown of Methodology

The key activities were:

- eSAT system implementation
    - Development of an eSAT Module that enables eSAT functionality in terminal devices
    - Design and development of red meat industry applications using eSAT satellite technology
    - Implementation of a Printed Circuit Board (designated the 'Tasman board') based on the eSAT Module, sized to fit within livestock tags
    - Development and testing of prototype livestock tags and IoT devices using the Tasman board

- Partnerships with satellite operators
    - eSAT uses existing satellites of a type defined as Geosynchronous L-band or S-band Mobile Satellite Service (MSS). Operators include Space42, Viasat (including Inmarsat), Ligado, MexSat, and Echostar.

- Integration of the tags and devices into the end-to-end satellite systems
- Testing of operation at various global locations
- Cattle smart ear tag trials in Australia were conducted at Pinjarra Hills and Rockhampton, with detailed daily monitoring. Each trial included recording weather conditions, animal monitoring, and device performance metrics. Data was integrated into the Smart Paddock dashboard, enabling visualization of livestock movement and IoT sensor readings. Trial durations were 15 days at Pinjarra Hills and 13 days at Rockhampton. Environmental factors such as tree cover and solar exposure were documented to assess connectivity robustness and energy harvesting performance.

### 3.1.1 eSAT Module development

The eSAT Module uses a hardware platform combining radio, modem, and processing elements. The System-on-Chip (SoC) components providing the foundation of modules are continuously evolving with Moore's law type improvements, i.e., increased capabilities, lower Size, Weight, and Power SWaP), and lower price. Over the past 2 to 3 years the evolution among suitable SoCs has enabled the cost-effective, practical implementation of tags and other on farm sensors tags. As described below, the mass of suitable modules is well below 1 gram. Considering cost, an example market report authored by Mordor Intelligence describes the evolution of technology comparable to eSAT's processing and radio requirements, stating '*Manufacturing scale and integrated chipsets pulled average module prices below USD 3.00…' (Mordor Intelligence, n.d.)*. Note that satellite capable modules are not quite at this price point yet. However, the ongoing trend towards lower cost and lower SWaP will continue to improve the Benefit to Cost Ratio.

eSAT has partnered with a global leader in module development, enabling a competitive combination of size, weight, power, and cost, based on a state-of-the-art platform. Our partner provides a comprehensive set of programming tools enabling eSAT to efficiently implement both the eSAT Module and devices based on that module.

The development evolved as follows:

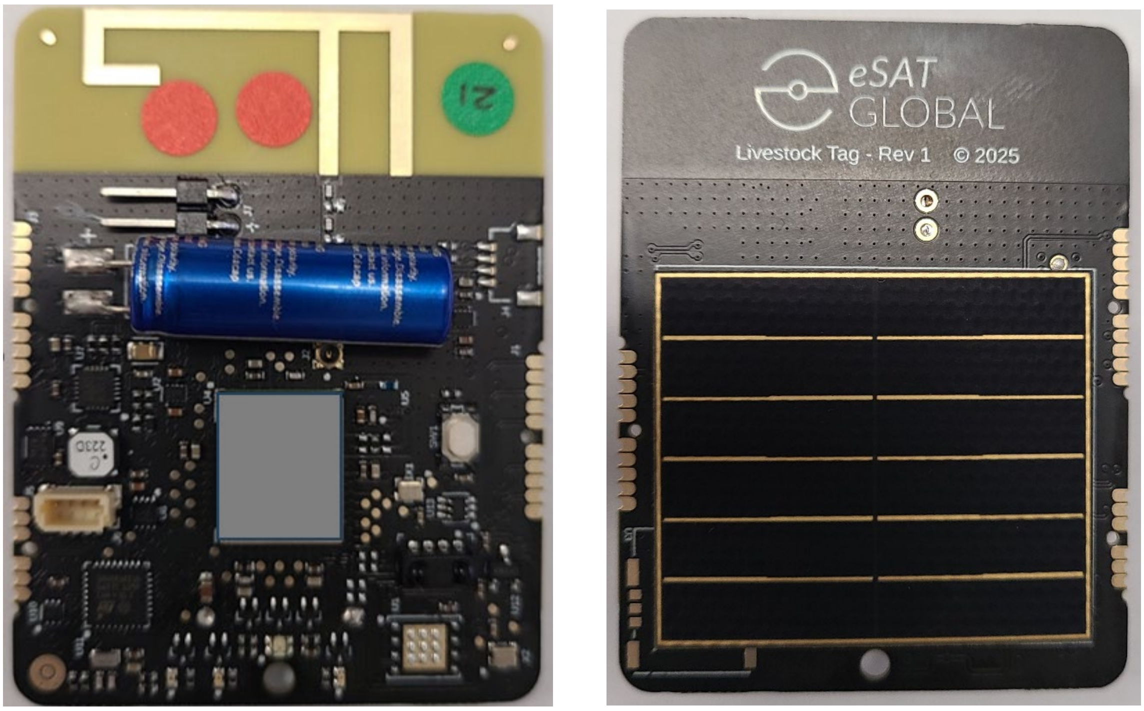
- Prior to the development partnership, eSAT implemented an early prototype (based on a Silicon Labs SoC), which combined processing and radio elements.
- eSAT worked with our module partner to validate compliance to eSAT's requirements, including the eSAT specification, i.e., the Common Air Interface.
- Hardware design changes enabled compliance to eSAT specific requirements, e.g., associated with signal phase stability. This was addressed by thermal isolation of the frequency reference (TCXO – Temperature Controlled Crystal Oscillator) on the Tasman board.
- Hardware and firmware were developed, integrated and tested.

During the development, eSAT has created a system, firmware, and software package that can be adapted to the changing hardware platforms. The eSAT Module enables compact implementation of the Tasman Board as shown in Figure 1. The dimensions of the module are ~11 mm x ~13 mm x ~2.4 mm. The small size and weight of ~0.65 grams of this module is comparable to terrestrial type modules making it suitable for a broad range of agriculture applications.

### 3.1.2 Tasman Board development

eSAT has worked with our partner, Smart Paddock, to create a Tasman Board enabled livestock tag. eSAT developed the Tasman Board (*Figure 1*) using the physical constraints of the Smart Paddock housing.

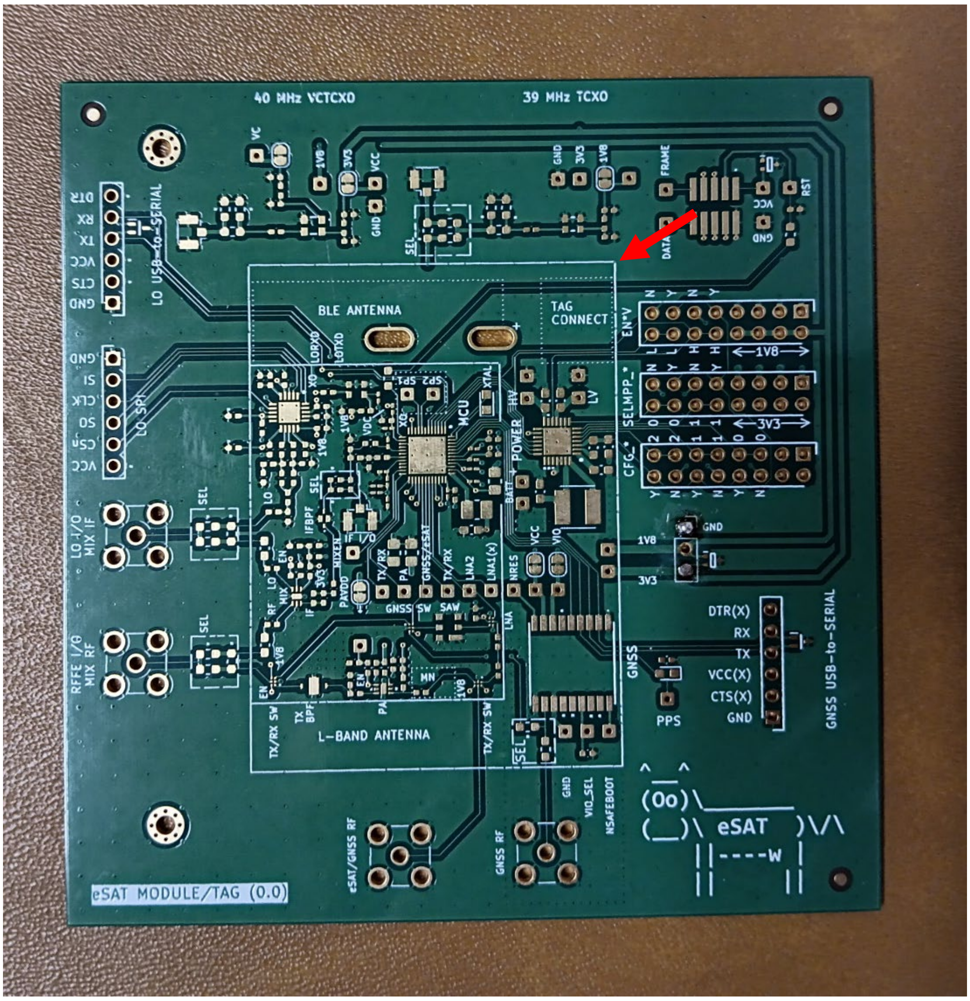
**Figure 1 eSAT 'Tasman' Board**




The Tasman board development involved several iterations:

- A development board using a Silicon Labs System-on-Chip illustrated in Figure 2, where the red arrow points at the area of the board corresponding to the livestock tag,
- Two revisions of a livestock tag sized board based on the Silicon Labs SoC, and
- Two additional revisions where the more recent is shown in Figure 1.

**Figure 2 Development Board**



### 3.1.3 Livestock Tags

The resulting tag can be attached to animals' ears as shown in Figure 3 and Figure 4.

**Figure 3 Animals during trials**

**Figure 4 eSAT tag on ear Rockhampton**

### 3.1.4 IoT Devices

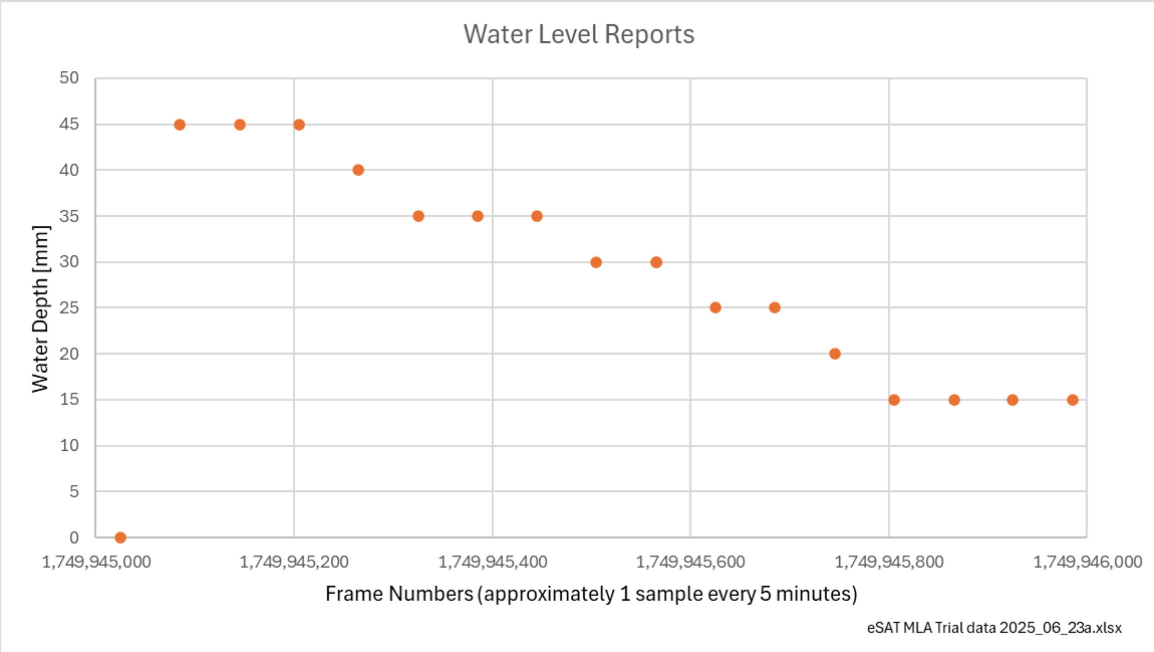
Prototype IoT devices were built with integrated Tasman Boards for the purpose of water level and soil moisture measurement trials, as shown in Figure 5 and Figure 6.

**Figure 5 eSAT prototype water level sensor on trough at Binalong**

**Figure 6 Soil moisture sensor Binalong**

The following chart shows an example of the data reported to the cloud while the sensor was placed in the water and then the water level was lowered.

**Figure 7: Water level reports**




### 3.1.5 Smart Paddock livestock location visualisation

The following screen captures illustrate the presentation of livestock locations in Rockhampton and Pinjarra Hills.

**Figure 8 Dashboard broad view of livestock in Rockhampton**

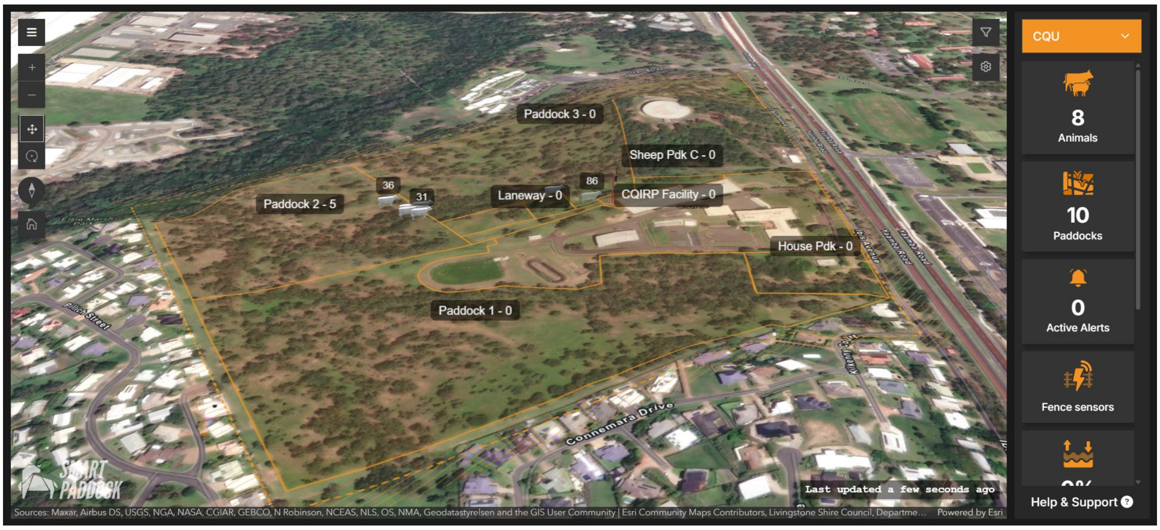


**Figure 9 Close in view of dashboard - livestock in Rockhampton**

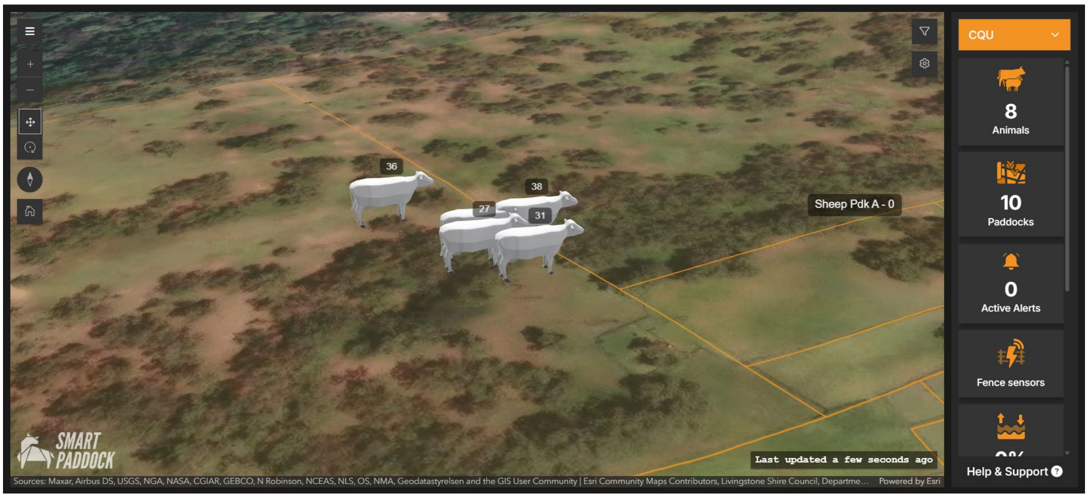



**Figure 10 Dashboard broad view of livestock in Pinjarra Hills**

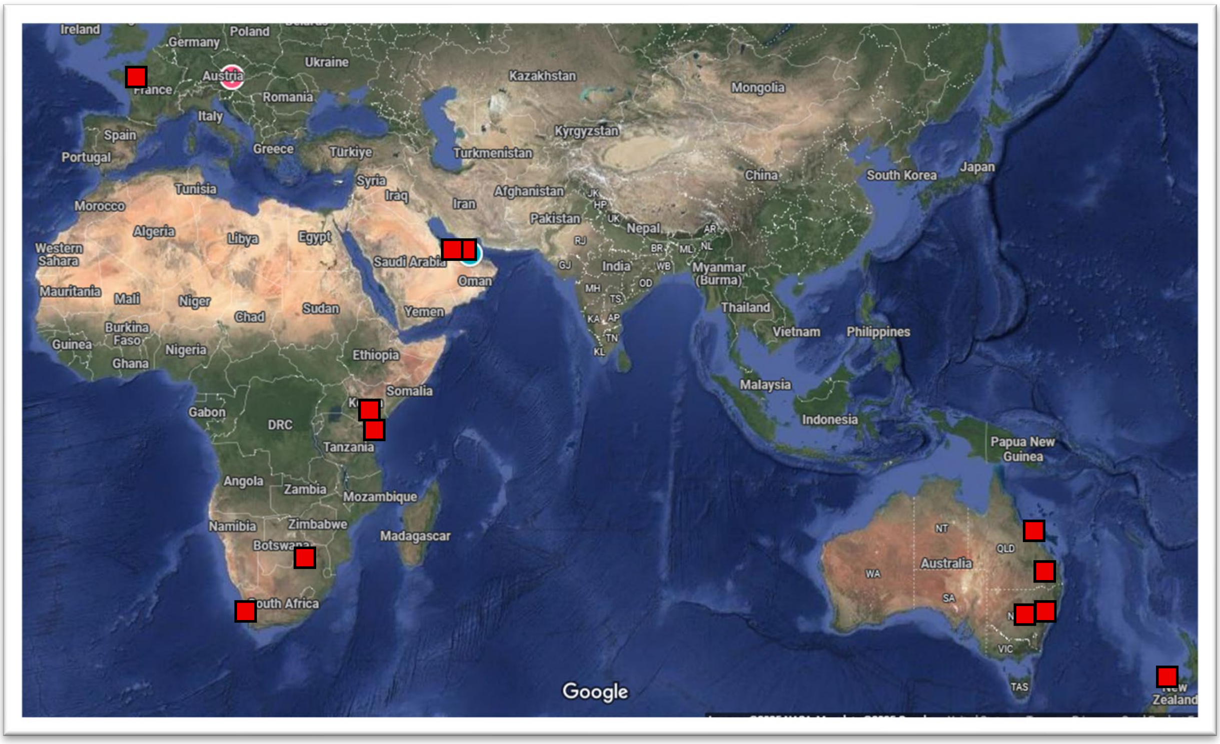

**Figure 11 Dashboard close view of livestock in Pinjarra Hills**

### 3.1.6 International Testing

Experimental tests were successfully undertaken in the following locations, as illustrated in Figure 12.

- South Africa, using Space42 but outside coverage
- Tanzania and Kenya, within Space42 coverage
- France, within Space42 coverage
- UAE, within Space42 coverage
- New Zealand; within Viasat coverage
- Australia, outside Viasat coverage
- Australia, trials within Viasat coverage at
    - Pinjarra Hills (Brisbane): where tags were attached to 10 cattle for ~15 days from June 15 to June 30.
    - Rockhampton: where tags were also attached to 11 cattle for ~13 days from June 17 to June 30.
    - Binalong: where the 2 Soil and 3 Water Depth Sensors were tested
    - Sydney: where the same Soil and Water Depth Sensors were tested

**Figure 12 Global sites for eSAT demonstrations and trials**



### 3.1.7 Australian Testing.

Figure *13* shows the locations of the Australian test sites.

**Figure 13 Australian sites for eSAT trials**


#### 3.1.7.1 Pinjarra Hills

These trials involved 10 commercial bulls, each approximately 3 years old, grazing at the Pinjarra Hills Research Facility of The University of Queensland (-27.5, 152.9), a 282-hectare research area in Brisbane, Queensland. On the afternoon of June 22, 2025, within an hour, Dr. Kieren McCosker, undertook the physical tagging of the bulls, by restraining each in a head bail of a CIA veterinary crush for a short period. Using an Allflex ear tag applicator, sensor tags were affixed in the middle one-third of the ear, between the rises in auricular cartilage. Dr. Gary Ballantyne and Dr. Martin Clark prepared the tags for application. Mr. Rick Somerton (eSAT) and Mr. Edouard Riotot (Viasat representative) observed the process.

Following the tagging, the bulls were allowed to free-graze in Paddock 23/4, which was over 95% open ground and featured two permanent water points, i.e., a single water trough and a large dam. The paddock's terrain was undulating with gradients of up to 25%. The elevation varied 30 meters within the paddock.

After completion of the test programme Dr. McCosker removed the tags from the animals.

#### 3.1.7.2 Rockhampton

The Rockhampton study area covered 8 hectares, consisting of approximately 60% open ground and 40% moderate tree cover. The paddock included both flat and sloped sections; however, all areas were considered to have a clear line of sight to satellites (when tree cover was not considered). Ten heifers from the CQIRP facility were selected for the trial. Each heifer was fitted with an eSAT/Smart Paddock tag and a store-on-board GPS collar developed by CQ University, then released into the trial paddock. The cattle were monitored daily for welfare requirements and to assess performance of the tracking devices.

CQ University removed the tags from the animals at the end of the trials.

#### 3.1.7.3 Binalong and Cammeray

The study site for the water and soil moisture IoT devices was initially located at Jarmelo, a cow calf operation 37km's Northwest of Yass. Two soil moisture monitors were located in an open field with a direct view of the satellite. Two Water Depth Sensors were located on a trough in the steel cattle yard with direct view of the satellite. It was found that the prototype IoT devices (developed as test units for the Tasman Board IoT trials) required continual monitoring and manual reset as a consequence of a software bug. Noting the issue was with the sensors themselves and not the Tasman Board, the devices were relocated to Cammeray in Sydney where their operation could be more conveniently reset and continuity of the satellite performance trials maintained.

### 3.1.8 Data Analysis

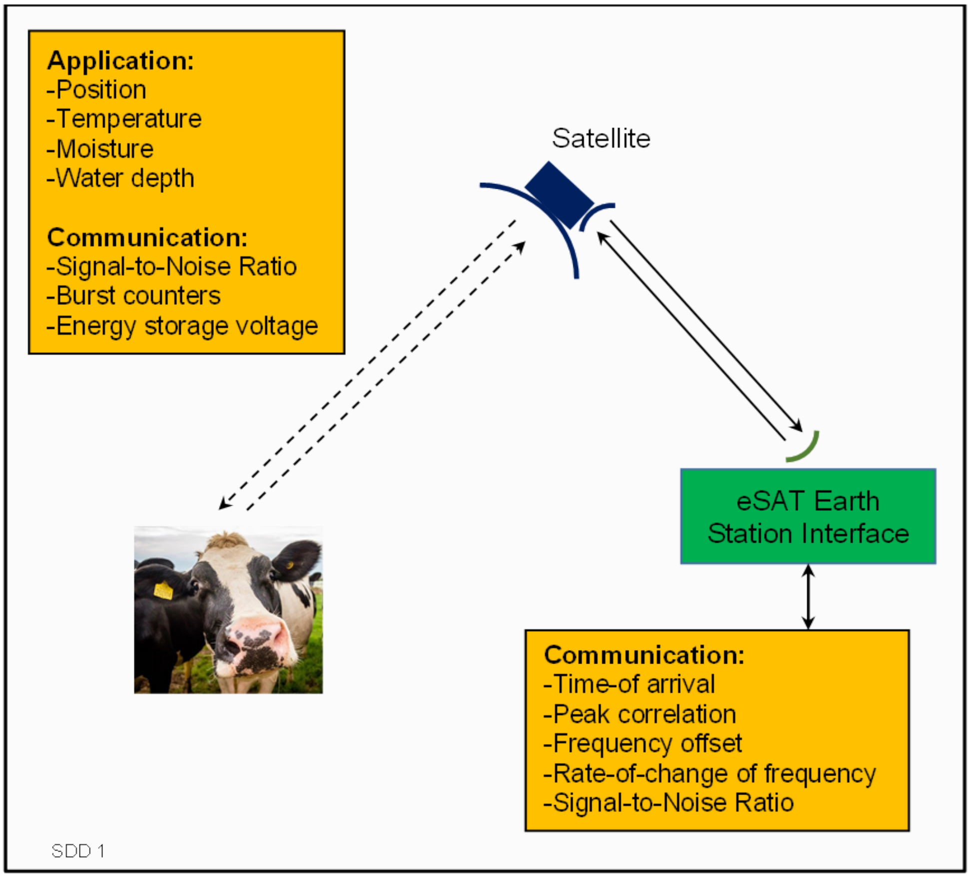
Two categories of satellite performance data were monitored during the trials, as shown in Figure 14.

- Application related metrics, such as the water depth of a trough, and location of tagged cattle and:
- Communications related metrics, such as the Signal-to-Noise Ratios estimated in the received signals.

In addition, the following data related to the trial operating environment and animal locations was also collected:

- Topography, with specific note of any possible satellite obstruction by hills etc.
- Tree coverage, providing an indication of possible shadowing of the satellite signals.
- Weather, where rain, temperature, and sun hours per day could impact performance.

Figure 14 Data communicated during trials




Application Metrics: Four application related metrics were collected and communicated in the trials. Commercial products are likely to use different and many more sensors. However, the number of bits to be communicated in terms of range and step-size with the sensors in the following table are representative.

Table 1 Data usage for metric communication

| Metric | Range | Step Size | Number of bits |
|---|---|---|---|
| Location Fix | Global | 0.6 m | 51 |
| Moisture | 0% to 100% | 0.1% | 10 |
| Temperature | -50C to +90C | 0.1C | 11 |
| Water Depth | 0 mm to 100 mm | 5 mm | 5 |

These data levels and reporting frequencies are specific to the trial implementation which concentrated on the demonstration of reliable connectivity of ear tags and IoT devices. For commercial operation it is anticipated that many sensor types, e.g. temperature and movement sensors, with various reporting frequencies will be supported. Taking the data associated with locations as an example, there is significant scope for enhancement to suit particular user requirements.

- Lower precision representation may be sufficient in some circumstances, e.g., 39-bit representation (12 fewer bits) would have step-sizes of ~38 m (i.e., maximum quantization errors of ~19 m).

- Edge processing (in tags) could generate data-compressed profiles of animal movement, say, over the period of a day.
- When precise location is critical (e.g., to know which side of a fence an animal is on) measurements can be controlled appropriately, e.g., requiring high confidence. Note that the GPS receiver in the eSAT module is specified to have accuracy of 3.5 m in rural environments (using a definition called CEP50, i.e., 50% of fixes are within this radius).

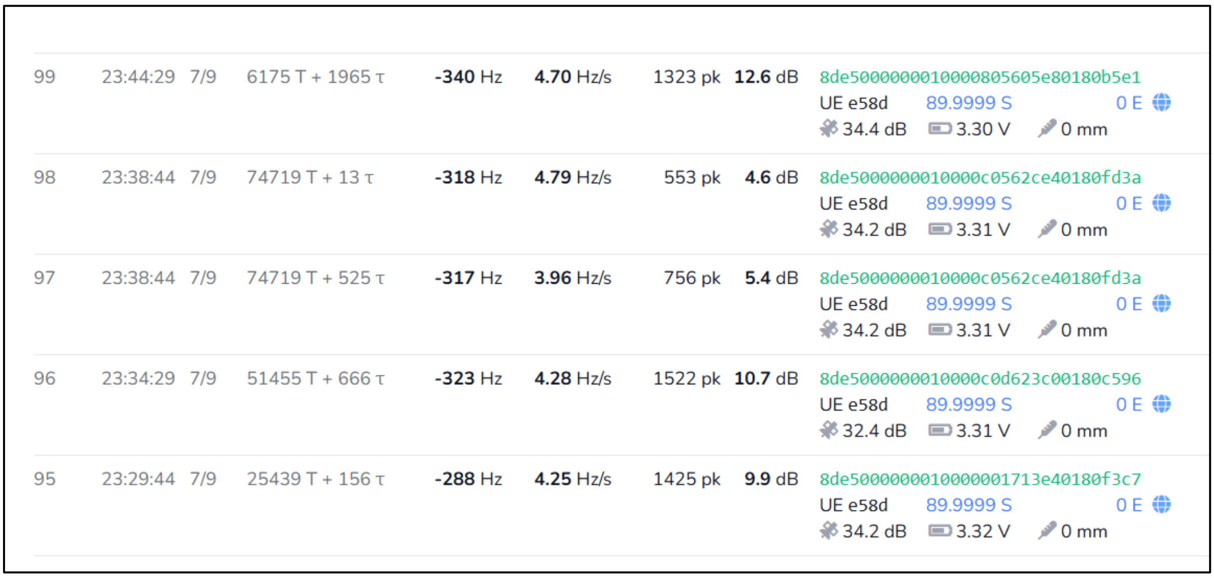
Using a 51-bit location fix for reference:

- The price for 10 message transmissions per day is ~AUD$4 per annum, or ~AUD$0.0011 per message.
- For different message types, the number of bits available for applications such as location information varies from 56 bits to 112 bits, implying the capacity of a message is sufficient for ~1 to ~2 location transmissions.
- In summary, for $4/year, 10 to 20 locations per day per animal could be reported. Note:
    - With data compression the number could be increased.
    - The number of fixes per day can be adjusted per animal.
    - Geofencing can be applied to generate more frequent reporting when, for example, an animal is near a boundary.

During the trials, the following communication metrics were recorded.

- Terminal measurements communicated to the network to enable measurement of performance during the trials.
    - Burst counters are inserted in each message to enable checking of whether each burst is received. The counters are incremented in the terminals and reported to the network. By observing received and missing counts, the network determines the Burst Success Rates, i.e., the ratio of bursts correctly received at the network to the number that were transmitted by the terminals.
    - Signal-to-Noise Ratios as seen by the terminals (describing their received signals) are also reported. These enable characterization of the forward link performance.
    - Energy Storage Voltage provides a metric enabling evaluation of the energy management by the terminal
- Measurements at the network receiver:
    - The Time-of-arrival is recorded and is based on the time at which a peak correlation between the received waveform and the known eSAT waveform occurs.
    - The Peak correlation is a measure of the amplitude of the peak, which provides an indication of the strength of the detection.
    - The Frequency offset says how far the received waveform is from the nominal frequency.
    - The Rate-of-change of frequency provides a metric related to performance in the presence of phase noise, which is a critical issue for narrowband communications.
    - The Signal-to-Noise Ratios as seen by the network enables characterization of the return link performance.

**Figure 15 Screen shot of typical reception at network**



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 99 | 23:44:29 | 7/9 | 6175 T + 1965 τ | **-340** Hz | **4.70** Hz/s | 1323 pk | **12.6** dB | 8de5000000010000805605e80180b5e1<br>UE e58d 89.9999 S 0 E<br>34.4 dB 3.30 V 0 mm |
| 98 | 23:38:44 | 7/9 | 74719 T + 13 τ | **-318** Hz | **4.79** Hz/s | 553 pk | **4.6** dB | 8de5000000010000c0562ce40180fd3a<br>UE e58d 89.9999 S 0 E<br>34.2 dB 3.31 V 0 mm |
| 97 | 23:38:44 | 7/9 | 74719 T + 525 τ | **-317** Hz | **3.96** Hz/s | 756 pk | **5.4** dB | 8de5000000010000c0562ce40180fd3a<br>UE e58d 89.9999 S 0 E<br>34.2 dB 3.31 V 0 mm |
| 96 | 23:34:29 | 7/9 | 51455 T + 666 τ | **-323** Hz | **4.28** Hz/s | 1522 pk | **10.7** dB | 8de5000000010000c0d623c00180c596<br>UE e58d 89.9999 S 0 E<br>32.4 dB 3.31 V 0 mm |
| 95 | 23:29:44 | 7/9 | 25439 T + 156 τ | **-288** Hz | **4.25** Hz/s | 1425 pk | **9.9** dB | 8de5000000010000001713e40180f3c7<br>UE e58d 89.9999 S 0 E<br>34.2 dB 3.32 V 0 mm |

Figure 15 shows the data presented as each burst is received at the network. This example relates to water depth measurement. The green values are the data content.

Scaling assumptions were evaluated by extrapolating from 20 tags to thousands of tags distributed across Australia using propagation models and link budgets. Known limitations include variability in antenna orientation and environmental shadowing. Bias from small sample sizes was acknowledged, and future trials will incorporate larger datasets to improve accuracy.

## 3.2 Performance Evaluation

Performance is evaluated in terms of the robustness of connectivity seen by end users. Performance metrics include Burst Success Rate (BSR) and Message Success Rate (MSR). BSR measures the success of individual transmissions without retries, while MSR accounts for retransmissions using Automatic Repeat Request (ARQ). Burst Counters track transmission attempts, and Signal-to-Noise Ratio (SNR) indicates link quality. These terms are explained at first mention for clarity.

A meaningful measure of robustness is the probability that a message is communicated correctly across a link (the Message Success Rate), e.g., from a livestock tag directly through a satellite to the cloud. As this section concludes, the Message Success Rate is configurable, and as the later results show, Message Success Rates of 99% are achievable. As discussed in the following, Burst Success Rates are adequate when they exceed, say, 50%. This enables the Message Success Rates to be practically set to the desired level. The achieved Burst Success Rates (89.7%) were well above the required rate.

Several factors influence robustness, including:

- The link margin, a difference between the power available for a link and the power needed to operate nominally in ideal conditions, e.g., no shadowing,

- The propagation environment, where factors such as satellite elevation angle, obstructions, fading due to multiple paths, and
- The protocols applied to retransmit information that has been received incorrectly (or not at all).

A key enabler of robustness is the availability of two-way connectivity which allows the network to automatically request retransmission of any missed information. This form of error control is called Automatic Repeat Request (ARQ) and is widely used. (eSAT has patented forms of ARQ that are specifically aimed at efficient operation in the satellite environment.) An advantage with ARQ when considering performance is that there is essentially no limit to robustness, i.e., by requesting retransmissions more times, a message will eventually get through. (An additional benefit is that receivers can remember the failed received signals and combine them to improve the probability of determining the content.)

For the purposes of the discussion here, the ARQ approach is assumed to be driven by a single parameter, N, the maximum number of tries at a transmission before giving up. Consider the two metrics mentioned above:

- Message Success Rate (MSR): where MSR is the success rate expected after applying retransmissions
- Burst Success Rate (BSR): where BSR is the success rate expected without applying retransmissions

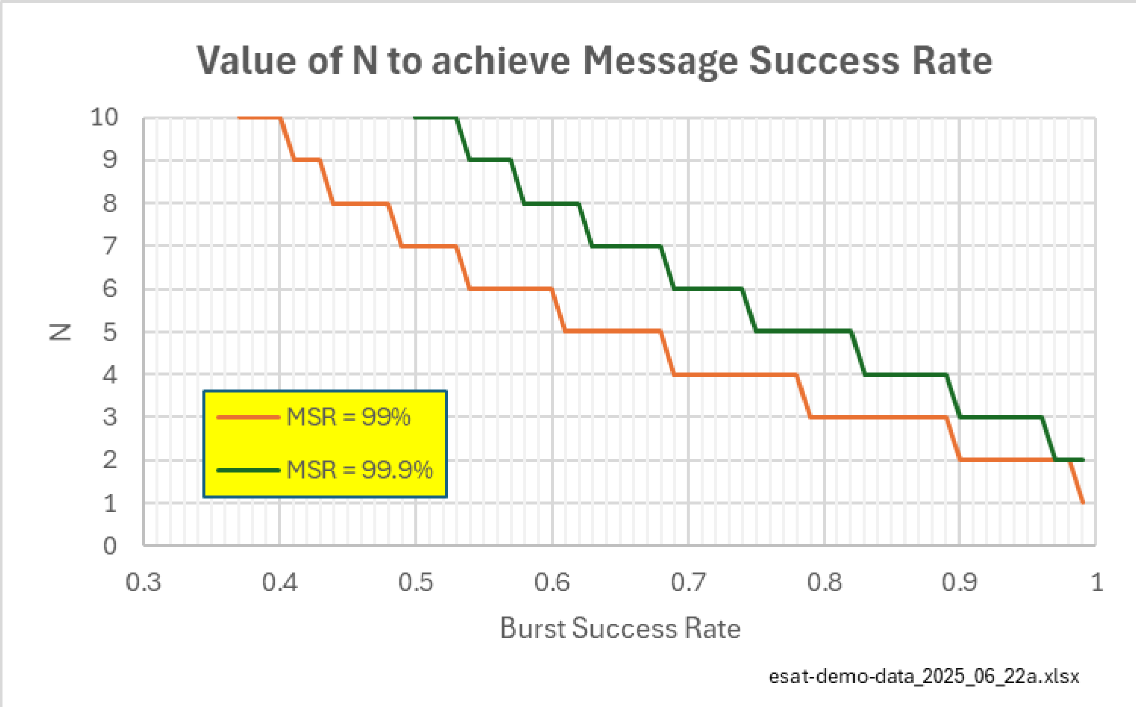
The Message Success Rate defines the robustness. Another benefit of two-way connectivity is the ability to manage Quality of Service, i.e., the Message Success Rate can be selected (and matched to applications). Let's consider two possibilities: 99% MSR and 99.9% MSR:

- The maximum number of retries is set to N.
- The individual probability of a successful transmission is the BSR.
- Assuming independent transmissions, successful acknowledgements, and no combination of received waveforms, the MSR and BSR can be related by:

$$MSR = 1 – (1\text{-}BSR)^N$$

This relationship can be used to determine N for the selected MSR values as shown in the following:

Figure 16 Message Success Rate control




As such, two-way connectivity Message Success Rates of 99% (and above) are comfortably achievable with Burst Success Rates above 80%, and possible with lower Bursts Success Rates, e.g., 50%.

# 4. Results

## 4.1 Module development

eSAT has implemented eSAT functionality on the eSAT Module. The module has performed well and has met the requirements related to enabling eSAT operation over satellites. eSat's development partner has confirmed capacity to meet future volume production.

## 4.2 Tasman board development

The Tasman board directly supports livestock tracking and can be used as the connectivity platform for IoT devices. The following are key characteristics:

- Mass of the populated board, including test connectors etc.: 13 grams
    - Estimated mass without test connectors etc.: 12 grams
- Mass with housing and pin (as on animal): 28 grams
- Dimensions (to fit in Smart Paddock housing): 44 mm x 59 mm x 5 mm (excluding supercapacitor)
    - 11 mm thickness including supercapacitor
- Energy management (for tags)
    - harvesting is based on a solar cell (30 mm x 35 mm)
    - storage uses a 100 Farad capacitor
- The energy management did not perform as well as anticipated. The number of transmissions peaked at 13 per day and should have been closer to 30. After the trials, eSAT studied the issues that arose in the energy collection, storage, and usage. This work resulted in much better performance than was achieved in the trials.

## 4.3 Livestock tag and IoT device development

Livestock tags and IoT devices were built and delivered for testing in the trials.

## 4.4 Trials and performance

The primary goal of the trials was to verify that connectivity could be reliably established through direct links via a satellite.

Communication functionality was established within a few hours of delivery. The robustness of the connections was shown during tests over a period of ~10 days. Test requirements involved periods of 7 days and a set of probabilities of data delivery.

### 4.4.1 Australian trials

The following conditions were noted at the test sites and during the trials.

- Topography: In all locations the slope of hills, gullies, etc. was well below the satellite elevation. As such, there was negligible impact from topographic shadowing.

- At Pinjarra Hills and Rockhampton, the tree coverage was roughly 10-20% of the area, and there are few shadowing buildings. The volume of data was insufficient to draw any conclusions regarding shadowing.
    - Note that shadowing by trees is likely to have significant impact only when the trunk is obstructing the line-of-sight to the satellite.
    - Also note that the eSAT system enables switching to different satellites in the event of prolonged obstruction.
- During the trial the weather was generally fine with direct sunlight available on most days. An exception was Tuesday June 17 when there was rain and overcast conditions all day in Rockhampton. The lack of sunlight had a significant impact on the energy harvesting by the tags, significantly reducing the volume of data collected.
    - Note: this is an important issue that requires further investigation and probable design changes in the path to a production tag.
- The temperature throughout the trials ranged from 9°C to 28°C in Rockhampton, 8°C to 25°C in Brisbane, -2°C to 15°C in Yass, and 7°C to 22°C in Sydney. These temperatures are all within the range within which performance should not be impacted, and no degradation due to temperature was noted.

In summary, the impact of overcast days on energy harvesting is the only observed environmental concern.

### 4.4.2 Global experience

The trial results show that Message Success Rates could comfortably operate at 99% or higher, i.e., the Burst Success Rates are above 80%. The Burst Success Rates at the various locations are shown below.

**Table 2: Burst Success Rates**

| Location | Satellite Condition | Burst Success Rate |
|---|---|---|
| Random orientation, Johannesburg | Outside coverage | 97.7% |
| Drive to Kruger Nat'l Park | Outside coverage | 96.5% |
| Capetown | Well outside coverage | 92.5% |
| Overall Dubai | Inside coverage | 98.6% |
| Trials - Livestock Tags | Inside coverage | 87.1% |
| Trials - IoT | Inside coverage | 93.7% |
| | esat-demo-data_2025_06_24a.xlsx | |

Note:

1. The trials have confirmed eSAT's ability to provide robust and efficient connectivity in a variety of locations, including beyond the normal conditions for commercial operation. That is, all cases show that Message Success Rates of 99%, would be easily achievable. See Figure *16*.

2. Examining the cases tested:
    a. Random orientation of tags and driving with tags in random locations within vehicles result in similar performance.
    b. With significantly reduced link margin (as in Cape Town where we operated outside of satellite coverage) the performance is noticeably degraded.
    c. The livestock tags had the lowest Burst Success Rate. The nature of the link in this case has not been studied in detail, but the presence of a large obstructing head, perhaps 40% of the time, is likely to be a contributor indicating that the 87.1% burst success rate is very reasonable.
3. The eSAT system is oriented around link margin of ~15dB. This enables robust performance in all tested cases. In many cases it is likely that the line-of-sight between the terminal and the antenna was obstructed, or that the terminal antenna gain in the direction to the satellite was low. A such, secondary paths (via reflected signals) are likely to be significantly improving the success rates. This is consistent with expected levels of secondary paths, i.e., 8 dB to 12 dB are typical.

## 4.5 Data Analysis and Interpretation

The topics addressed include:

- Estimation of expected performance across Australia: based in a combination of the link budget, a propagation model, an antenna gain model, and calibration based on the trial results
- Phase noise of reference oscillators
- Energy harvesting and storage in the tags

### 4.5.1 Livestock Tracking Performance Expectations

The quality of satellite data transmission depends on numerous factors. This section introduces a model that estimates an eSAT tag's communication performance across Australia. The model will enable ongoing optimization of service quality while simultaneously minimizing cost, i.e., reducing resource usage (power and bandwidth).

The model's purpose is to establish a process for ongoing refinement, i.e., it will improve and be adapted as more data is accumulated. Message Success Rate (MSR) provides a meaningful metric when defining the performance of Smart Livestock Tags and other on farm sensors. A reasonable target value of MSR could be 99%. The Message Success Rate can be derived from Burst Success Rate (BSR) as discussed earlier, noting that Burst Success Rate provides a more useful indication of performance. Burst Success Rate depends on the following:

1. The link budget relating the tag's Effective Isotropic Radiated Power (EIRP) to the margin
2. The distribution of tag EIRP in the direction towards the satellite, i.e., primarily the tag's antenna gain pattern and the statistics of its orientation over time
3. Significant close-in shadowing such as the animal's head and ear
4. The propagation conditions beyond the close-in shadowing, e.g., trees and buildings

The following approach is applied to develop the model of the propagation characteristics of the eSAT tag-to-satellite link.

1. Take the $10^{th}$ percentile EIRP over the antenna pattern, i.e., where 90% of the EIRP values are lower.
    a. The rationale for this approach is to select a reference point at which the antenna is well pointed and the shadowing etc. is minimized. This will be approximately the same for different applications, e.g., on an animal's ear or on an IoT device. Degradation in the form of pointing error and propagation losses can then be defined relative to this point.
2. Evaluate the link budget at that point, i.e., determine the link margin, using a defined EIRP and bearer combination.
3. Use the EERS (Extended Empirical Roadside) model (Goldhirsh & Vogel, 1998) to estimate the fade depth as a function of margin and satellite elevation.
4. Apply a model of the antenna gain distribution and the antenna orientation to generate a distribution of antenna gain.
5. Combine the antenna gain distribution and the EERS distribution to create a model for the link, EERS-A.
6. Apply an offset to account for the close-in shadowing, yielding EERS-AT.

### 4.5.2 Link Budget with good pointing and minimal obstructions

A Link Budget's purpose is to quantify and combine metrics that drive the Signal-to-(Noise plus Interference) Ratio at a receiver. A threshold in this ratio can then be applied to define the margin in the link.

Note that the satellite G/T parameter (i.e. G-over-T or the measure of how well a satellite or ground station can receive weak signals) used in the link budget are taken from public material and thus may have some errors relative to actual/confidential values.

The tag EIRP and G/T values are based on antenna measurements in free space, i.e., without close-in objects such as a cow's head.

The key derived outcome of the link budget is the Margin. This metric described the excess capability of a link relative to operation at a performance threshold. The threshold used corresponds to 99% Burst Success Rate. For example, the 18.01 dB Margin in the return link in the table below means that the terminal's transmit power in close to the best direction (the $10^{th}$ percentile) is ~63 times higher than that needed to achieve the 99% Burst Success Rate.

**Table 3 Link Budget for trials**

| *10th percentile of UE antenna with Inmarsat 4F2 Spot Beam* | | |
|---|---|---|
| **Link Budget** | **Forward** | **Return** |
| EIRP [dBW] | 25.00 | -12.00 |
| Slant Range [km] | 39550.73 | 39550.73 |
| Carrier Frequency [MHz] | 1550.00 | 1643.00 |
| Path Loss [dB] | 188.20 | 188.70 |
| RIP [dBW] | -163.20 | -200.70 |
| G/T [dB/K] | -26.08 | 12.70 |
| Boltzmann [dB J/K] | -228.60 | -228.60 |
| C/No [dBHz] | 39.32 | 40.60 |
| Information Bit Rate [bps] | 22.85 | 22.85 |
| Ebi/No [dB] | 2.00 | 2.00 |
| UE Antenna Pol. Loss [dB] | 3.00 | 3.00 |
| Overhead for Pilot etc. [dB] | 3.00 | 3.00 |
| Channel Est. loss [dB] | 0.30 | 0.50 |
| Other losses [dB] | 0.50 | 0.50 |
| Ec/No required [dB] | -28.10 | -28.10 |
| Ec/No achieved [dB] | -11.17 | -10.10 |
| Margin [dB] | **16.93** | **18.01** |
| Ebi/No achieved [dB] | 18.93 | 20.01 |
| | *link_budget_esat_v.1.021.xlsm* | |

Note:

1. The nominal satellite EIRP is 25 dBW, where this is distributed equally as a beacon GBCW (sinusoidal) reference signal and a single traffic TCH signal (22 dBW each).
    a. For the trials the actual satellite EIRP used was 33 dBW for each of the sinusoid and TCH bearers (and this was adjusted for in evaluation of compliance to the link budget). Error rates were measured in the other direction, so these high levels were inconsequential.
2. The $10^{th}$ percentile of tag EIRP is ~18 dBm (with -12 dBW EIRP).
3. The tag antenna is not circularly polarized, so a 3 dB loss is applied in the path to/from the polarized satellite.
4. The traffic signal in both directions contains a Pilot set at the same level as the data. (The relative levels are parameterized, i.e., they can be adjusted.)
5. The resulting margin estimates are around 16.9 dB (Forward) and 18.0 dB (Return).

### 4.5.3 EERS Propagation Model

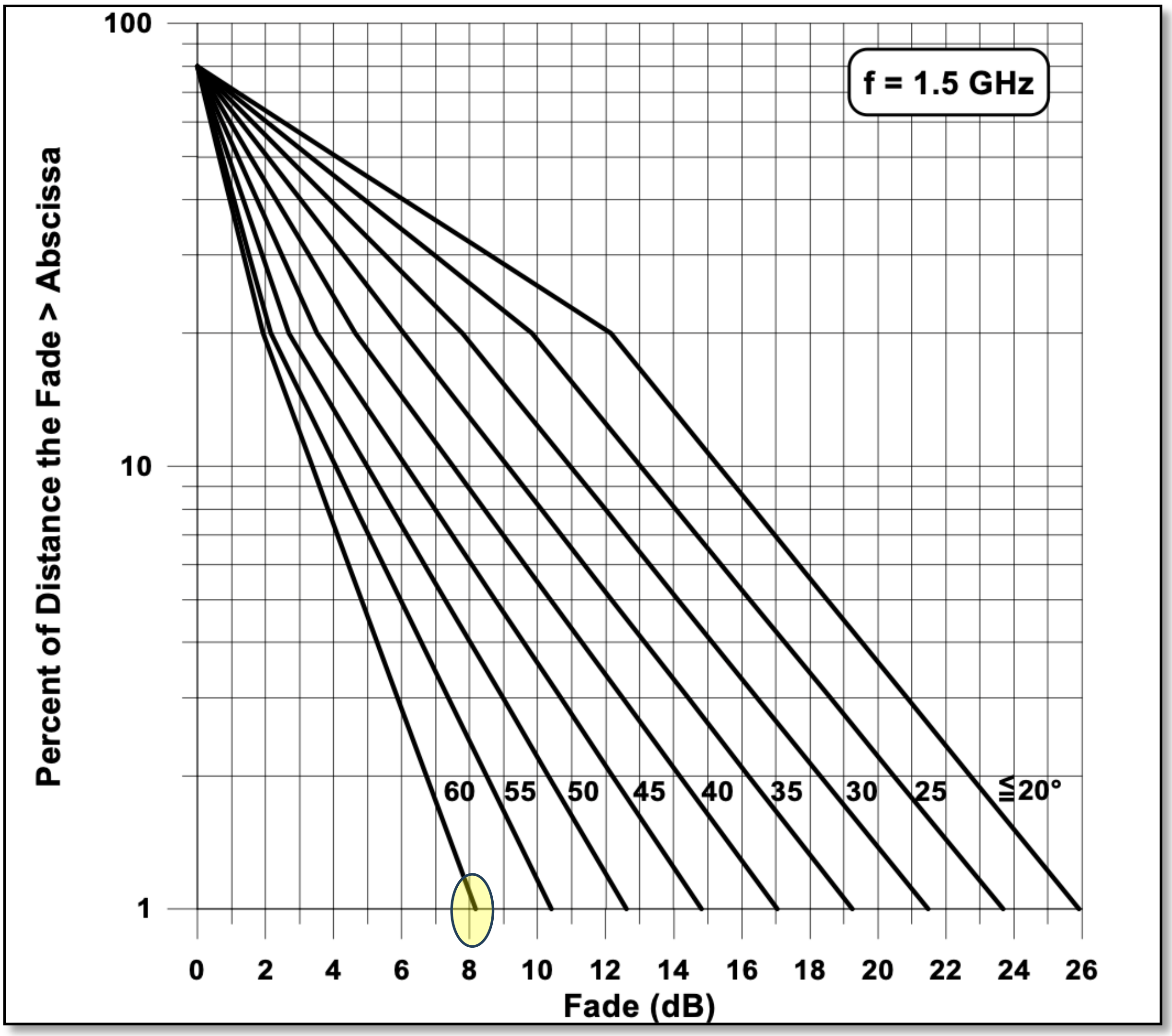
Propagation models are selected to match specific situations. The EERS model (Goldhirsh, 1998) is a suitable basis for livestock tracking and other agricultural applications, as it is primarily based on the impact of trees and occasional buildings on satellite links.

The EERS propagation model estimates the fade depth at which some percentage of gain samples (over time or space) of a link will be below a defined value. For example, for the point identified in the chart below:

- With these conditions
    - Typical tree shadowing
    - At 1.5 GHz

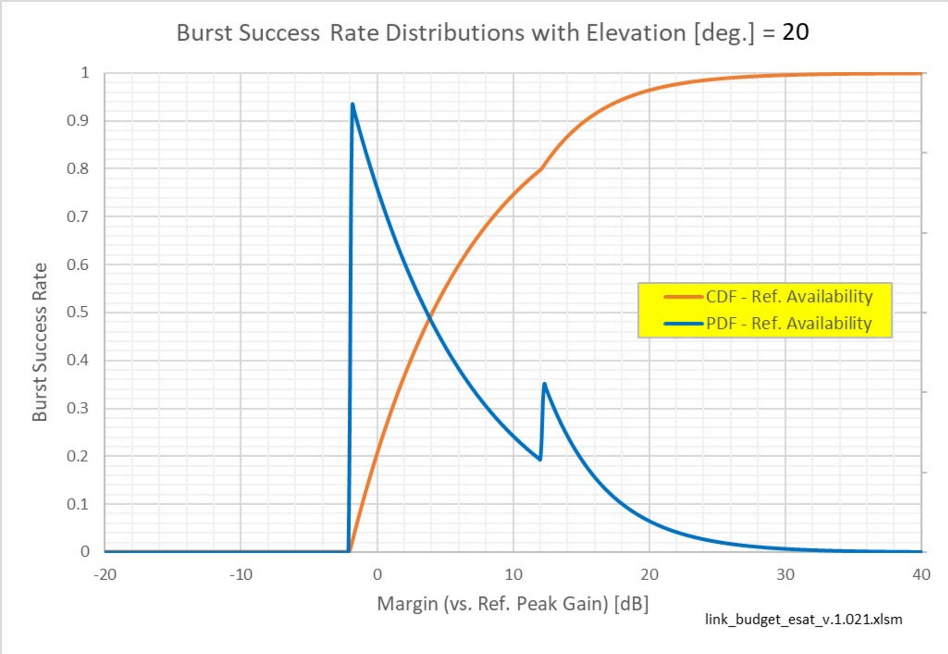
    - At 60 degrees satellite elevation
- The probability of greater than 8 dB attenuation (relative to line-of-sight) is 1%.

**Figure 17 Family of cumulative fade distribution curves derived from application**




The characteristics in the EERS chart can be converted into Probability Density Functions (PDFs) relating Burst Success Rate to Margin. The following chart shows the results of the conversion to Burst Success Rate vs. margin for 20 degrees elevation at 1.5 GHz. Note that 20 degrees elevation is a reasonable indicator of the edge of coverage.

**Figure 18 EERS PDF (Burst Success Rate vs. Margin)**




### 4.5.4 Antenna Gain and Combined Distributions

The gain distribution of the antenna used on the Tasman board has been evaluated in free space and characterized by a normal distribution in the dB-domain, with -7.1 dB average gain with 4 dB standard deviation. Over the complete sphere with equiprobable orientation, the gain distribution is as shown in Figure 19. Figure 20 shows the Margin required to achieve Burst Success Rates above 80% at 20 degrees elevation.

**Figure 19 Combined Antenna and Propagation PDFs**

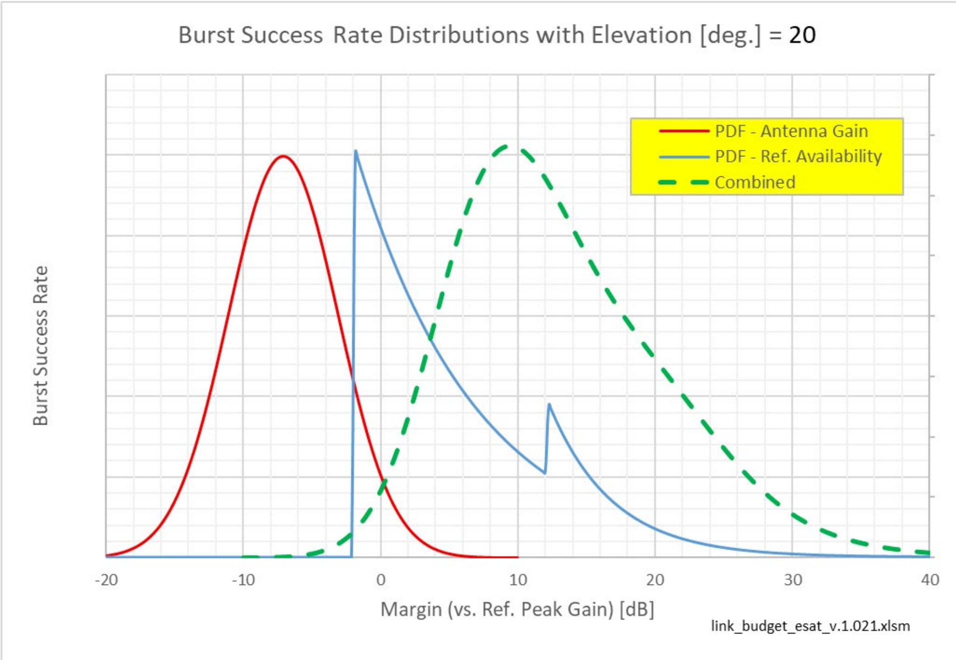
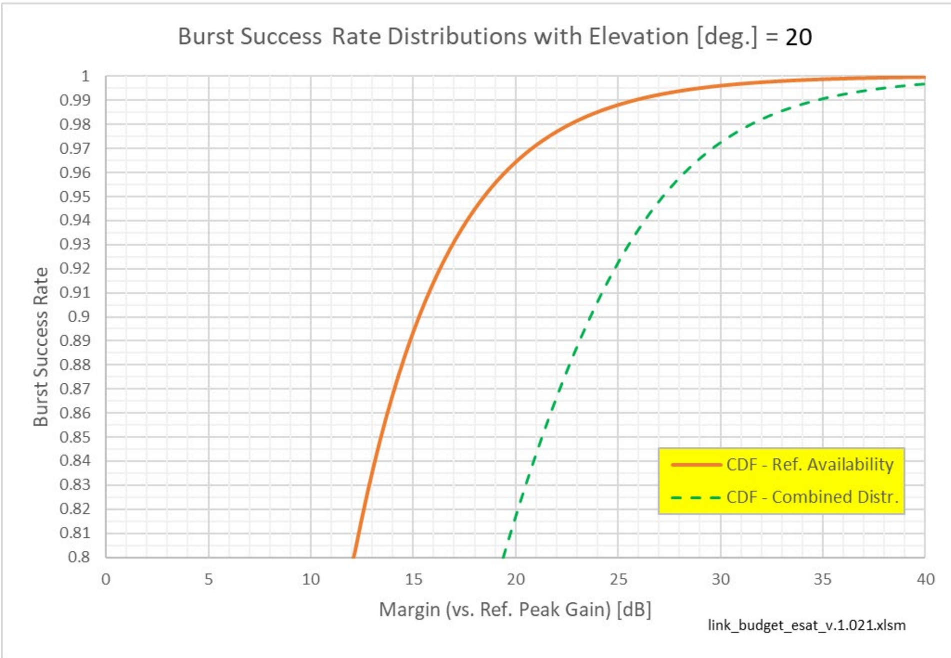
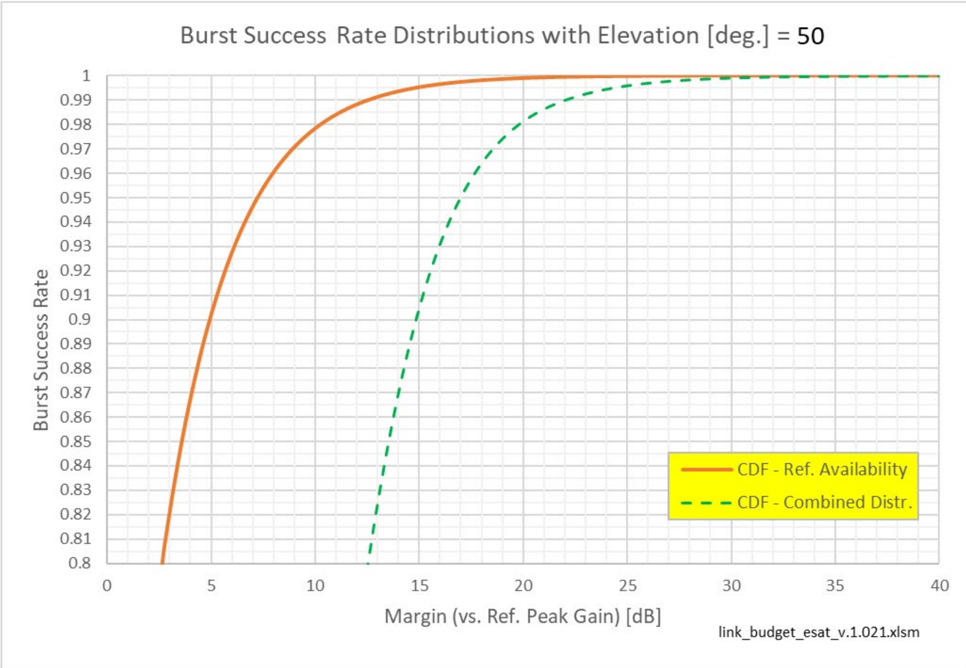



**Figure 20 Cumulative Distributions (20-degree elevation)**




Across the test sites in Australia, the satellite elevation varied from ~50 to ~65 degrees. Hence, operation at 50 degrees is representative (and a little conservative). Figure 21 shows the estimated performance at 50 degrees elevation. The combined cumulative distribution is denoted EERS-A, i.e., EERS combined with the antenna pattern generating Burst Success Rate estimates.

**Figure 21 Cumulative Distributions (50-degree elevation)**




### 4.5.5 Observed Performance

The measured Ebi/No for the return link, separated into IoT and livestock tracking groups, are shown in Figure 22.

- At the 10th percentile Ebi/No is ~19.5 dB for both the tags and IoT devices, corresponding to a 17.5 dB margin.
- As shown in Figure 23 the tags are operating ~3.6 dB worse than the EERS-A model.
    - Note that the model does not include the impact of the close-in shadowing by the head and ear, so the 3.6 dB is an estimate of the impact.
- The IoT performance is ~1.5 dB from the model.
- Performance in tests in Dubai last year provide another data point (slightly better than the EERS-A model). These tests used the same antenna and ~60 degrees elevation. The tests involved mostly pedestrian or other positioning of the devices by people (not animals or IoT applications).

**Figure 22 Measured Ebi/No for tags and IoT devices**

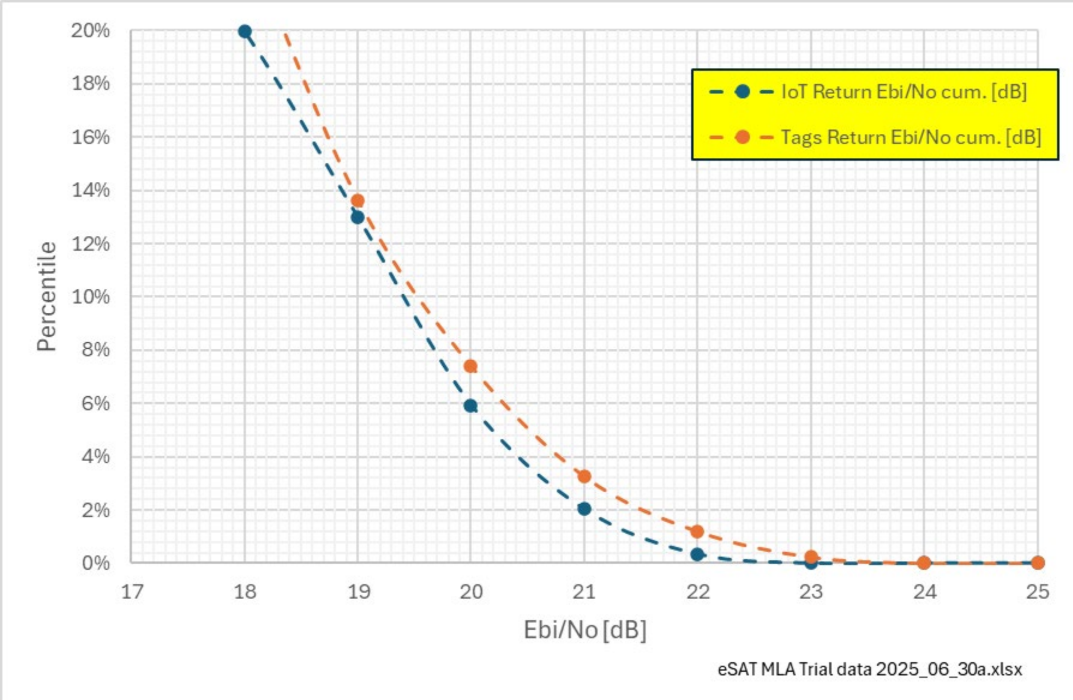
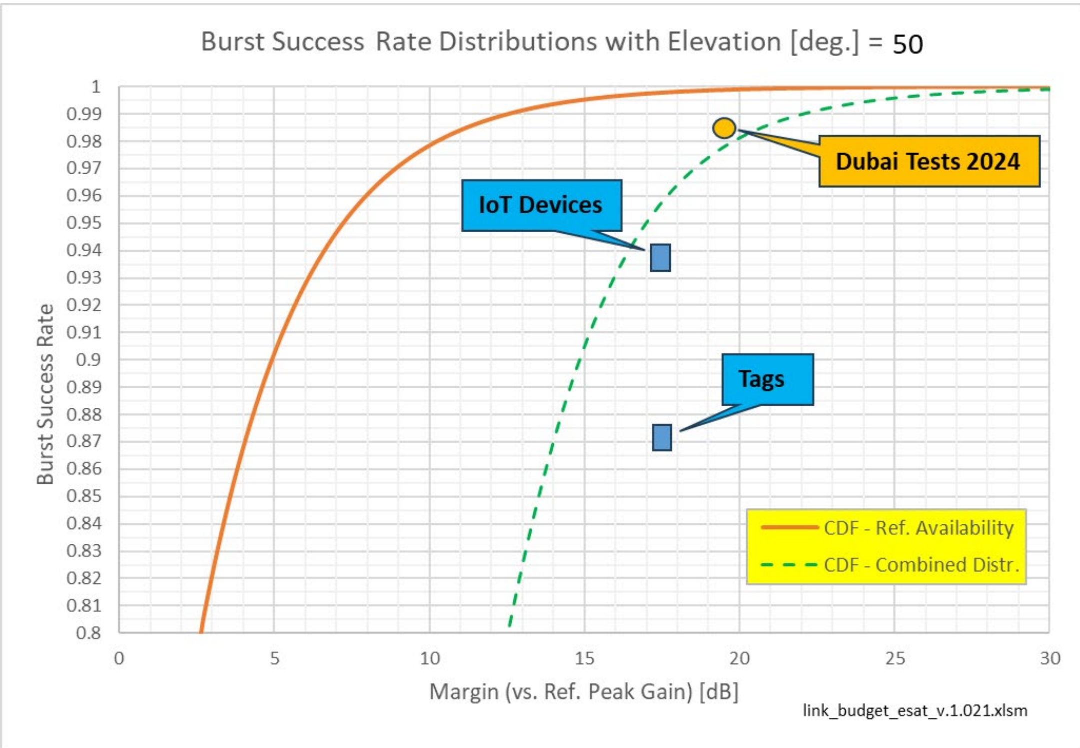



**Figure 23 Performance vs. EERS-A Model**



Notes:

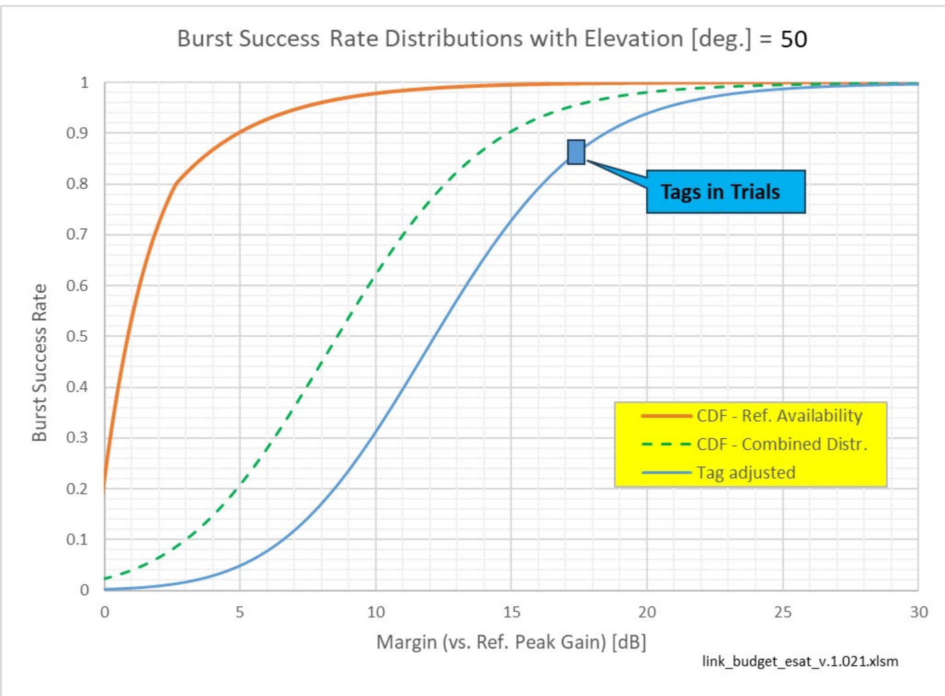
1. There were ~1,200 reports from tags. These reports should be close to independent, given the different animals and continuously varying orientation by each animal. Assuming independence, the standard deviation from the actual average would be ~1%. That is, the measured average of 87.1% is likely to be close to the actual average (for the conditions).
2. For the IoT devices, the number of reports is much higher, at ~6,000. However, the number of distinct orientations is much lower as the devices are typically stationary. Perhaps a total of 10 to 20 different orientations were applied. This means that the overall average Burst Success Rate of 93.7% has higher variance.

### 4.5.6 Extrapolation Across Australia

Assuming the EERS model (combined with fixed head/ear shadowing degradation) remains applicable, the following chart shows the worst-case expected performance across Australia. This is based on a satellite elevation of 35 degrees, which is derived from a minimum elevation with the satellite at the equator (40 degrees – see Figure 26) and allowing 5 degrees for the impact of inclination. Figure 24 shows the estimated Burst Success Rate vs. Margin for 50-degree elevation, assuming the degradation with tags (ear/head etc.) is constant in dBs of margin. This creates a distribution denoted EERS-AT, where the impact of the tag environment is included with EERS-A.

Figure 25 shows the case with 35-degrees elevation, i.e., the worst case in Australia (Tasmania and Southwest Western Australia).

**Figure 24 Performance vs. EERS-AT model at 50 degrees elevation**



### Figure 25 Performance vs. EERS-AT model at 35 degrees elevation

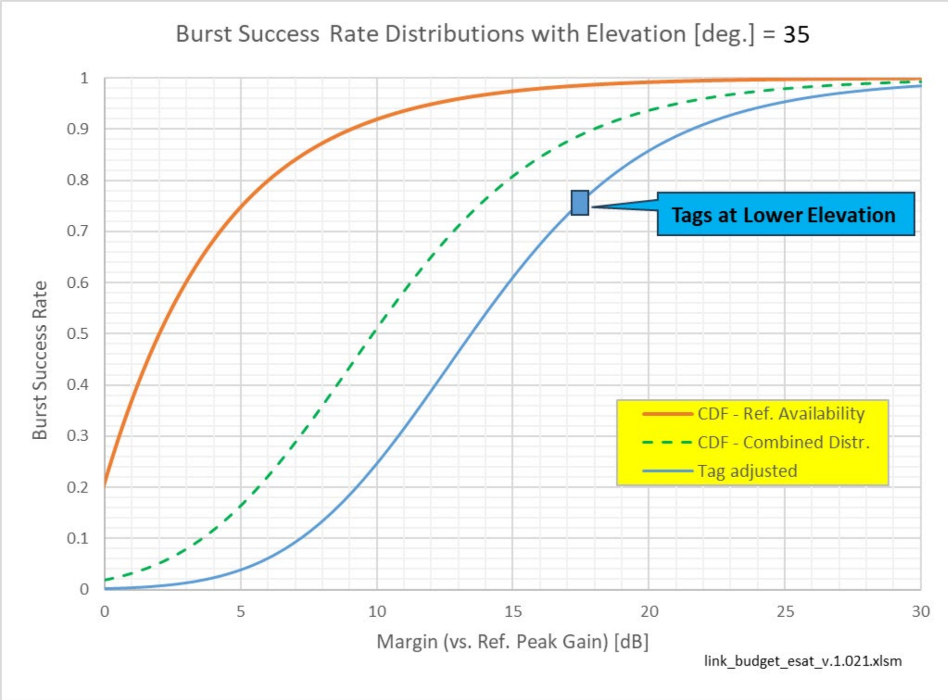


**Figure 26 Australian coverage with satellite elevation**

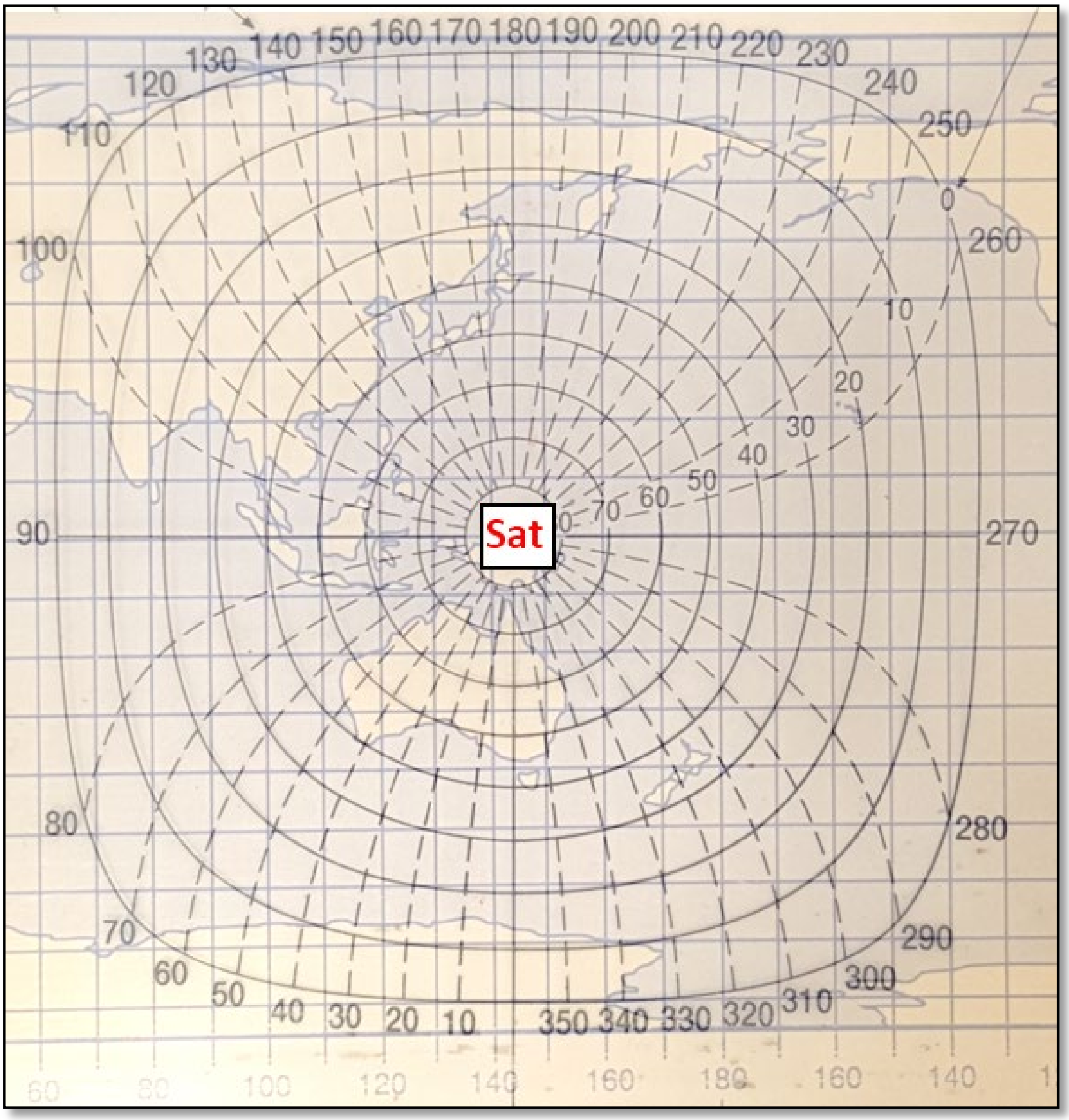
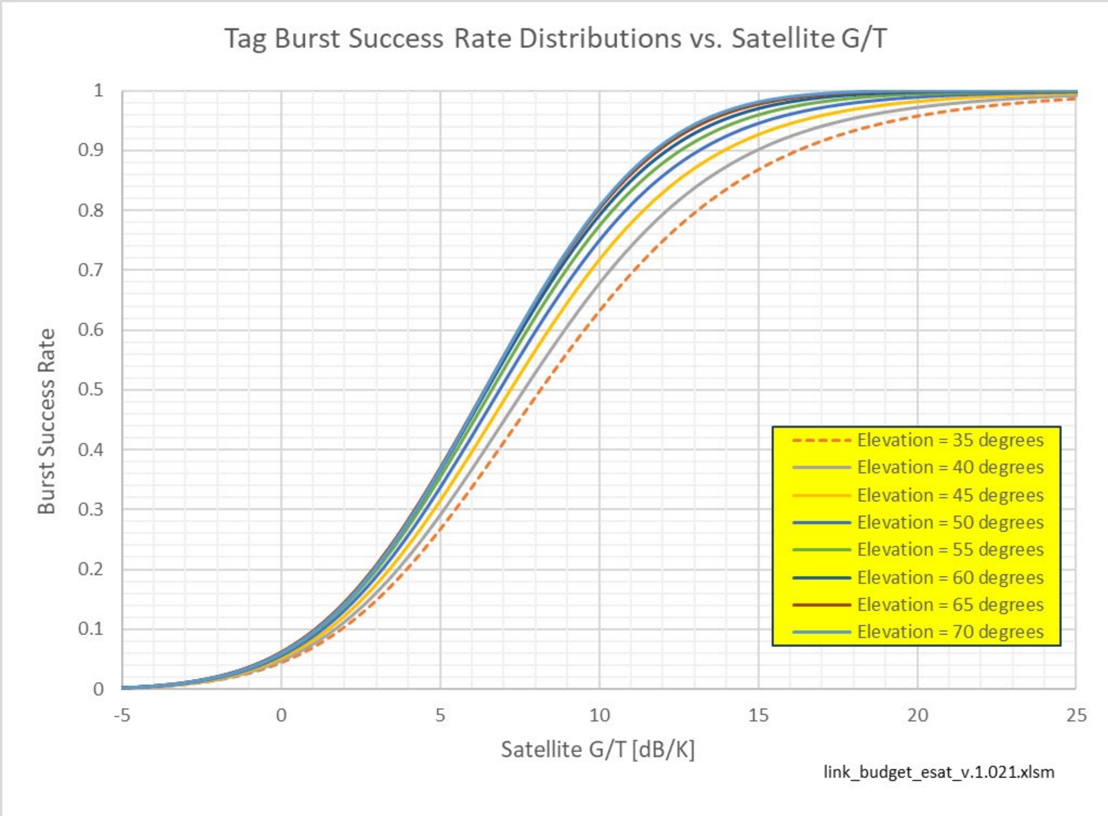



Figure 27 shows the estimated Burst Success Rates for tags as a function of satellite G/T for the range of elevations in Australia. The term G/T (Gain over Temperature) provides a measure of a satellite's ability to receive small signals, i.e., its sensitivity.

**Figure 27 Tag Burst Success Rate vs. Satellite G/T at various elevations**




Satellites can synthesize beams of different sizes within coverage areas. The size of the beams has an impact on the G/T. For the smallest beams (which have the best sensitivity) the G/T can vary from ~11 dB/K to ~21 dB/K for different satellites. For the trials, the link budget value G/T was 12.7 dB/K.

Noting that the Message Success Rate can be set arbitrarily as a function of the Bursts Success Rate (by retransmitting as needed), the question arises as to what a reasonable repetition rate might be. A reasonable model, perhaps, is a factor of 2, corresponding to Burst Success Rate = 0.5 in Figure 27. Note that this corresponds to satellite G/T between 6 dB/K and 9 dB/K depending on elevation.

#### 4.5.6.1 Status of the propagation model

1. A model is developed to enable estimation of Burst Success Rates across Australia.
    a. The model (EERS-AT) is based on a combination of a model used in the satellite industry and the measurements from the trials.
        i. The spread (standard deviation) of Burst Success Rates for tags in the trial areas is estimated at ~1% relative to the measured average of ~87%.
        ii. The spread for IoT devices is larger. The number of independent samples was insufficient to generate a meaningful estimate.
    b. The model should be viewed as a preliminary form of a tool that will evolve as more data is collected. The data collected in the trial is close to anecdotal. The EERS model, though, has proven to be useful in a variety of environments related to other satellite systems.
2. The characteristic in Figure 25 is the current estimate of performance at the edges of coverage in Australia.

### 4.5.7 Reference Oscillator Stability

A key driver to the practicality of the eSAT system is the close-in (~1 Hz to ~10 Hz) phase noise. That is, low data rates (around 20 bps) result in sensitivity to phase errors over periods in the order of large fractions of seconds. Change in frequency with temperature is a significant contributor to close-in phase noise, so eSAT device designs include means to reduce the thermal impact, e.g., when a power amplifier is on and heating. This includes flexibility in the location of TCXOs (Temperature Compensated Crystal Oscillators).

TCXO's are useful in Earth located satellite communication modules due to their ability to maintain stable frequency performance across wide temperature ranges. This stability is essential for ensuring accurate time synchronization and signal transmission in critical systems. TCXOs provide high frequency stability, with fluctuations controlled between, say, ±0.1ppm and ±2ppm, which is helpful for the precision of GNSS positioning and timing services. They also offer resistance to temperature changes, ensuring high frequency stability in environments with temperature fluctuations. Additionally, TCXOs have low power consumption, making them suitable for applications that require high performance and long working time, such as portable devices and battery-powered systems.

The Tasman board has multiple options for the location of the TCXO, where two were used in the trials: (1) inside the module (which contains the power amplifier), and (2) approximately 2 cm from the module at the corner of the board as shown in the following figure (yellow squares).

**Figure 28 TCXO Locations**

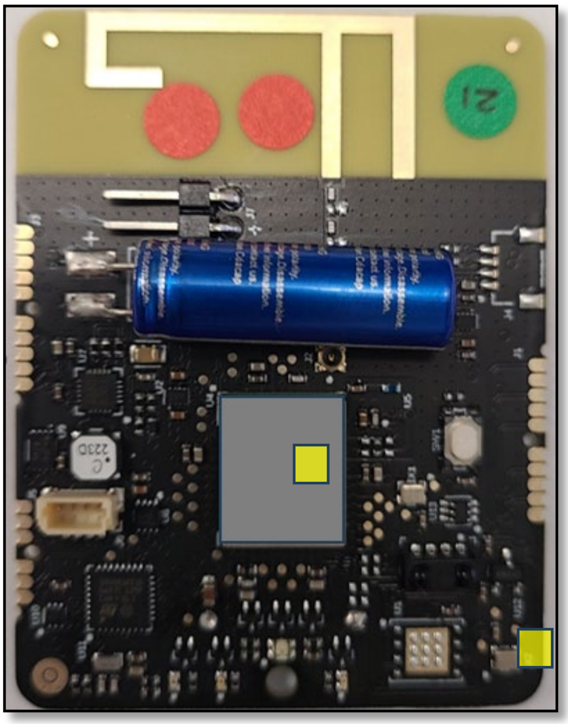
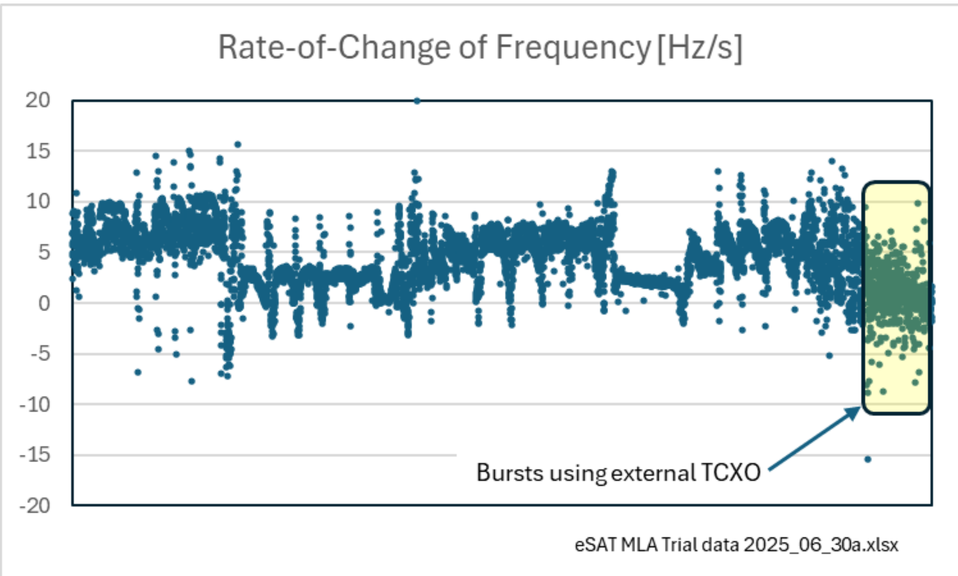


Figure 29 shows the difference in chirp (rate of change of frequency) seen at the network receiver during transmission from the Tasman boards.

**Figure 29 Impact of TCXO location**




Note:

1. The estimates include errors from multiple sources (e.g., estimation error) so the values shown are not a direct measurement of the chirp.

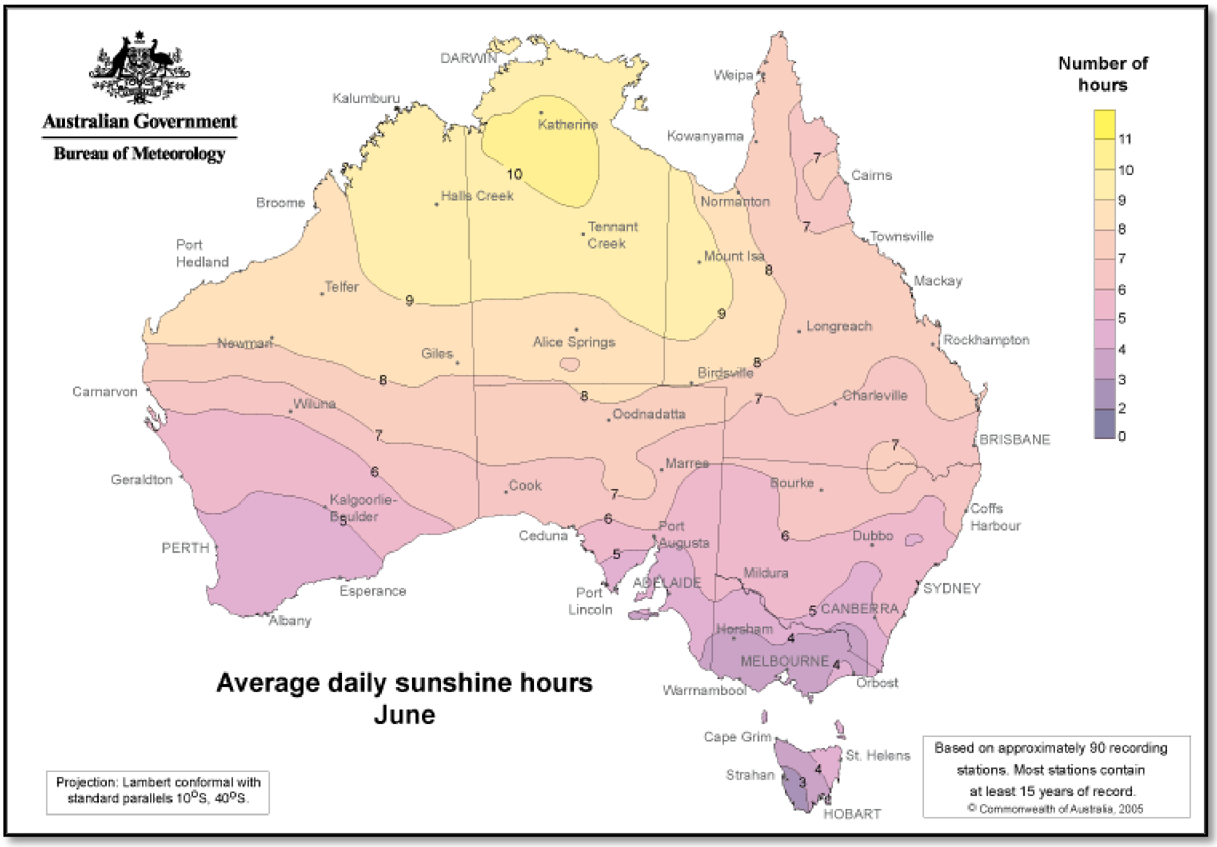
2. The values in the chart are consistent with laboratory tests.
3. The transmissions with the TCXOs inside the module use 'pre-heating' (to partially mitigate the variation).
4. The impact of phase noise is low, i.e., tenths of a dB degradation.

### 4.5.8 Energy Harvesting and Storage

The Tasman board is powered by a solar cell and uses a supercapacitor for storage. For the IoT devices a battery is used. The tags were configured such that they would transmit as often as possible, given the energy harvested and stored.

The chart below, from the Australian Bureau of Meteorology (Bureau of Meterology, 2025) shows the average daily sunshine during June in Brisbane and Rockhampton is at least 6 hours per day. The least average daily sunshine in Australia (defining the worst case) is at least 2 hours per day in Western Tasmania.

**Figure 30 Average Daily Sunshine Hours (June) - Source:** *(Bureau of Meterology, 2025)*



The following table shows a tag energy budget for an average day in June in Brisbane.

**Table 4 Tag Battery Life estimates**

| | |
|---|---|
| Maximum Charging Rate (solar cell pointed at full sun) [mW] | 189 |
| Stored Energy (max voltage to threshold voltage) [J] | 132 |
| Minimum charging time [Min] | 11.6 |
| Energy used per transmission [J] | 14.5 |
| Efficiency [%] | 50% |
| Transmission per charge | 4.6 |
| Sunlight average June and July [Hours per day} | 6 |
| Effective directivity to sun | 10% |
| Charges per day | 14.9 |
| Expected Transmissions per day | 68.9 |

This budget suggests that on an average day a tag should be able to transmit over 50 messages.

- A key unknown in the budget is the ‘effective directivity’. This is the proportion of time during which the solar cell is effectively pointed directly at the sun, where 10% is a rough estimate based on a combination of the following while considering a tag on an animal’s ear:
  - At least 50% of the time the solar cell will be shaded, i.e., in the wrong 180-degree orientation.
  - The elevation of the sun will typically mean that there is an angular offset from peak directivity in the vertical plane (i.e., in a line orthogonal to the surface of the solar cell).
  - Similarly, in the horizontal plan, the angular offset from peak directivity will vary.
  - The ear and head could also shadow the solar cell at times.

The peak number of messages sent in a day during the trials was 13 per tag. After the trials, eSAT studied the issues underlying the energy shortage, and has resolved the issue. As such, operation in commercial tags with the same solar cell and supercapacitors as those in the trials is anticipated to be applicable throughout Australia. If more storage is desired, an option would be to use a battery rather than a supercapacitor for energy storage.

The following narrative describes the range and context of possible refinements:

- The implementation of energy storage and management involves trades between cost, mass, device lifetime, and message transmission rate.
- The implementation for the trial used a supercapacitor (with a mass of ~3 grams) with energy storage capability of ~200 Joules.
- The expected energy usage for a cycle including a GPS fix and transmission (as implemented in the trial) is ~30 Joules, implying ~6 reports per charge.
- Using more energy efficient forms of both the GPS fix and the transmission, the energy usage could be reduced to ~7 Joules per cycle.
- Taking a worst-case sustained period without charging (implying heavy overcast with no breaks) for, say, 10 days, the reporting rate could be 2-to-3 messages per day using the energy efficient approaches. This scenario is suggested as a target requirement.

- As an alternative, high temperature batteries that would work comfortably in Australian conditions could be used, with storage of ~800 Joules with mass of ~8 grams.
    - This would enable up to 10 messages per day for over 10 days or 3 messages per day for a month in the absence of charging.
    - The price and weight impacts mean this option is viewed as an existence proof that such a robust solution is possible, rather than as a recommendation.

# 5. Conclusion

The successful development and demonstration of eSAT's next-generation, low-cost direct-to-satellite communication system represents a major step forward for enabling digital transformation across the Australian red meat and livestock industry. This project has shown that ubiquitous, reliable, and affordable IoT connectivity—long identified as a critical barrier to adoption of precision livestock technologies—can be realistically achieved at scale at a much lower cost than competing systems, thereby enabling higher Benefit-to-Cost Ratios (BCR) for producers.

The trials and propagation scaling modelling show that eSAT's ultra-low-power, two-way satellite system can support wide-ranging on-farm sensor types and operate more affordably then previously possible across Australia's diverse environments. These outcomes will further unlock opportunities for improved livestock management, enhanced animal welfare, strengthened traceability, and more efficient use of labour and natural resources.

A key insight from the project is that whole-herd connectivity is technically feasible at much lower costs than previously possible with the potential to shift livestock monitoring from selective or sentinel-based approaches to universal coverage. For producers, this means affordable real-time access to individual animal behaviour, location, and health indicators—information that has repeatedly been shown to drive measurable improvements in productivity, grazing efficiency, reproductive performance, and biosecurity outcomes. The ability to combine livestock data with broader IoT systems such as water level sensors, satellite enabled pasture data, weather stations and asset trackers further enhances the value proposition and supports more automated, resilient agricultural operations.

The project also identified several important learnings and areas for further development. Energy harvesting performance under low-sunlight conditions emerged as a key engineering challenge, particularly for ear-tag applications reliant on solar charging and supercapacitor storage. While post-trial analysis has produced solutions to improve energy collection and usage, further validation under diverse seasonal conditions will be essential. Similarly, although connectivity performance exceeded expectations, additional refinement of antenna placement, shadowing mitigation, and firmware optimisation will support even greater robustness and efficiency in commercial deployments. The propagation modelling developed through the project is promising but remains preliminary; expanding the dataset through broader geographic trials—particularly in more challenging environments such as Tasmania and parts of Western Australia—will strengthen predictive accuracy and support long-term optimisation.

Knowledge gaps also remain in relation to long-term durability, battery and supercapacitor lifecycles, and the performance of integrated sensor suites over multi-year device lifetimes. As modules progress towards commercialisation, standardised reference designs, documentation, and developer support will be required to enable widespread integration by AgTech solution providers. Further investment in large-scale field demonstrations, end-user training, and change-management programs will help producers build confidence in the technology and rapidly realise value from data-driven livestock management.

Overall, this project provides promising evidence that low-cost satellite IoT can fundamentally reshape the economics and practicality of digital agriculture. By closing the connectivity gap that has long constrained adoption, eSAT's technology positions the red meat and livestock industry to accelerate productivity gains, improve sustainability outcomes, and strengthen global competitiveness. Continued collaboration between technology developers, producers, research institutions, and supply chain partners will be critical to fully harness these benefits and ensure that the foundations established through this project translate into scaled up implementation onto enduring industry-wide impact.

## 5.1 Key Findings and Their Relevance to the Red Meat Industry

The research clearly demonstrated the feasibility, lower cost, and the robustness of eSAT's satellite network.

- eSAT has the potential to provide ubiquitous connectivity to animals throughout Australia.
- Total cost of ownership will be ~$15/year/animal initially and the price will subsequently drop as the advantages of volume are realized.
- The reliability of communication has been demonstrated with Message Success Rates around 99% or higher. Burst Success Rates averaged 87.1% for livestock tags and 93.7% for IoT devices.
- No roadblocks are seen in the path to commercialization. However, the following areas require additional work to ensure a quality product:
    - *Reliability:* The hardware design must ensure high reliability, i.e., long life (10 years, say), of the livestock tags.
        - Energy storage by batteries or supercapacitors must use components with long lifetimes at the temperatures in all Australian operating environments.
    - *Energy availability:* During full-day overcast conditions, transmission rates dropped by approximately 40%, highlighting the impact of solar energy harvesting limitations. This finding underscores the need for improved energy storage solutions. The energy accumulation and storage elements (solar cells and batteries/supercapacitors) will be selected to optimize the trade between reporting rate, mass, and cost.
    - *Communications robustness:* Several aspects of the design will be improved to increase communications reliability while lowering energy usage, e.g., optimizing the location and implementation of the antenna on the tag.
    - *Sensor and data processing:* Sensor readings on the tags will be interpreted within the tags to generate data related to health, reproduction, etc.
- During commercial operation, optimization will continue. Examples include:
    - The propagation model will be refined with data accumulated from operating tags. This will enable, for example, adjustments to power settings etc. to maximize the capacity and data reliability of the system.
    - Tag size will be reduced to broaden the number of species that could be supported, to lower costs, and to improve retention.

## 5.2 Functionality and Robustness of Connectivity:

The eSAT system is designed to operate anywhere in Australia, provided devices are not shadowed by buildings or similar obstructions. This widespread coverage is a significant advantage for the red meat industry, allowing for tracking and monitoring of livestock across vast pastures and remote grazing lands. The trials also confirmed that the connectivity is robust, with sufficient margins to achieve message success rates of 99% or higher. While a statistical propagation model was developed, further validation across the country, particularly in challenging areas like Tasmania and the Southwest of Western Australia, is ongoing to refine the model. High message success rates are critical for producers relying on accurate and timely data for herd management, disease detection, and theft prevention.

## 5.3 eSAT Module Development and Maturity of Tags:

The developed eSAT module provides the fundamental basis for commercial tags and IoT devices. This signifies a significant step towards bringing these solutions to market. The connectivity of the tags has been demonstrated to be robust, and their environmental specifications are consistent with Australian operational conditions. However, further evaluation and correction are required regarding the consistency of energy harvesting and energy storage is required. Addressing these power management issues is vital for the long-term viability and practicality of livestock tags in the demanding conditions of the red meat industry. Producers need devices that are reliable and require minimal intervention for power.

## 5.4 Size, Weight, and Power (SWaP) of Tags:

The current SWaP of the tag is compatible with existing tag housings, such as those from Smart Paddock. This compatibility allows for easier integration into existing industry practices. While the current size is acceptable, there is potential for further reduction, particularly for applications like sheep tags, with the extent of this reduction still to be determined. Smaller, lighter tags are less intrusive for animals and more durable in the challenging environments livestock inhabit, increasing the likelihood of producer adoption.

## 5.5 Price and Commercial Viability:

A critical finding is that the system will enable operation (tag and data service) at an annual total cost of $15 per year for basic services by 2027. This competitive price point is a major factor in driving broad producer adoption within the red meat industry, as cost-effectiveness is often a primary concern for agricultural businesses. Looking ahead, it is anticipated that module and device pricing will decrease further with technical improvements and increasing populations, although the rate of this price reduction is unknown. Continued cost reduction will make these technologies even more accessible to a wider range of producers, from small to large-scale operations.

## 5.6 Remaining Issues and Future Directions:

eSAT is continuing the development and the testing of its module. The tags developed were primarily the result of eSAT's engineering team and module partner. Commercial product implementations by third parties requires eSAT, as part of its ongoing R&D programme, to produce instruction and command sets, datasheets and reference designs typical of IoT module manufacturers. Furthermore, eSAT needs to develop and optimise firmware to automate much of the functionality and operation of the module allowing full mobility and functionality.

eSAT radio module operation to date has been using experimental authorisations. Prior to commercial operation eSAT modules must be approved for commercial operation as will devices using the module in each jurisdiction in which they are used. The eSAT module is based on an existing module with global authorisations.

Satellite enabling of the broadest range of new and existing Agtech solutions will require off the shelf hardware with industry standard documentation and support.

Early development of solutions is critical to early adoption and market traction. eSAT proposes to work directly with a small group of Agtech solution providers and lead customer producers. These partners will be guided by eSAT engineers to advance broader product(s) release. The learning experience of demonstrations and early field trials will provide feedback in development and for implementation of the support programme being developed for a support programme for developers and early adopters.

Addressing these remaining issues will be crucial for the widespread and seamless integration of eSAT's technology into the red meat industry, enabling enhanced animal welfare, improved operational efficiency, and more sustainable practices.

**Table 5 Summary of Key Findings**

| Topic | Resolved Outcomes (known) | Remaining Issues (unknown or partially known) |
|---|---|---|
| Functionality of tag and IoT connectivity via satellite | Will operate anywhere in Australia where devices are not shadowed by buildings or similar. | |
| Robustness of connectivity | Margin is sufficient to enable Message Success Rates of 99% or higher. Statistical propagation model developed but not validated throughout country. | Statistical model will be refined as new data is obtained. Tasmania and Southwest of Western Australia are the most challenging. |
| eSAT module development enabling device implementation | Module provides basis for commercial tags and IoT devices. | |
| Maturity of tag on path to production | Connectivity is robust. Environmental etc. specifications are consistent with Australian operation. | Energy harvesting and storage in the trials were inconsistent with the budget. Requires evaluation and correction. |
| Size, Weight, and Power (SWaP) of tag | SWaP is compatible with existing tag (Smart Paddock housing) | Tag size could be reduced, e.g., for sheep. Extent of the potential size reduction is to be determined. |
| Price | Enables operation (tag and data service) at $15/year | Module and device pricing will fall with technical improvements and increasing populations. The rate of price reduction is unknown. |

## 5.7 Benefits to industry

The successful development and validation of the eSAT direct-to-satellite communication technology within this project represent a significant breakthrough in low-cost satellite technology, unlocking a myriad of previously cost-prohibitive benefits for the Australian red meat and livestock industry. By providing affordable, reliable, and ubiquitous connectivity, eSAT's solution directly addresses the primary challenge highlighted by Trotter et al (Trotter, et al., 2018), i.e. the lack of commercially available, cost-effective Location and Behaviour Systems (LBS) for livestock. This project has effectively bridged that gap, transforming potential advantages into tangible, realisable outcomes.

The benefits span various facets of livestock production and value chain management, as detailed in the following sections.

### 5.7.1 Improved Grazing Management and Pasture Utilisation:

Low cost eSAT-enabled smart tags, providing accurate animal location data, empower producers to implement sophisticated grazing management strategies. This includes optimising pasture utilisation by monitoring grazing patterns in detail. Research indicates that such technologies can lead to a 5-15% improvement in stocking rates. (Millward, et al., 2020; Uden, 2025) Furthermore, facilitating practices like rotational grazing through precise location monitoring can increase forage mass by approximately 30% and enhance overall pasture health and sustainability (Anon., 2023).

### 5.7.2 Enhanced Animal Health and Welfare:

The integration of sensors within eSAT-connected smart tags promises the early detection of illness and distress, often days before clinical symptoms become apparent (Eadie , 2025). Changes in activity levels, feeding patterns, and rumination times can be monitored to identify animals requiring attention. This capability leads to more timely interventions, potentially reducing the severity of health issues, lowering veterinary costs, and minimising antibiotic use (Bailey, et al., 2018).

Activity monitoring systems have demonstrated, in a small sample size, the ability to identify up to 90% of animals in oestrus with 100% accuracy, a significant improvement over traditional visual detection methods (Eadie , 2025). Using activity monitoring systems also significantly improves reproductive management.

Beyond direct health benefits, the ability to remotely monitor livestock provides producers with invaluable "peace of mind".

### 5.7.3 Increased Biosecurity and Traceability:

In an era of increasing global focus on food safety and provenance, robust biosecurity and traceability systems are paramount. eSAT-enabled smart tags can provide the means for rapid and accurate tracing of animals. Accurate tracing is invaluable for effective disease outbreak management, smart livestock can reduce disease investigation times from days or weeks to mere minutes or hours (Animal and Plant Health Inspection Service, USDA, 2021). [The technology supports compliance with evolving traceability regulations, such as the USDA mandates for EID in certain cattle categories which are often prerequisites for maintaining access to both domestic and international markets.]

### 5.7.4 Reduced Mustering and Labour Costs:

The ability to know the precise location of livestock in real-time via GPS-enabled eSAT smart tags offers substantial reductions in the time, labour, and associated costs of mustering, especially across large and difficult terrains (Bailey, et al., 2018). Studies have shown that GPS tracking can reduce labour costs associated with livestock management by as much as 25%.

The automation of routine monitoring tasks further contributes to labour efficiency, allowing farm personnel to focus on other critical activities.

Remote water monitoring combined with remote pump and valve activation using satellite will reduce labour requirement and directly reduce the amount of fuel required to check water levels on large properties. Failure to monitor in a timely manner can have significant costs both in stock loss and animal welfare concerns with the potential to undermine social licence.

### 5.7.5 Theft reduction

Bailey et al highlight the potential for theft reduction. “Real-time tracking could also be used to reduce the incidence of stock theft. Movement patterns associated with being gathered and moved could be used to detect unauthorised herding and potential stock theft. When cattle are herded, the tracking pattern is more linear and less sinuous than free-ranging movement pattern. A monitoring system could alert managers when tracking data indicate livestock are being herded. If the herding was not authorised, the system alert could potentially allow managers to respond before the animals left the property.” (Bailey, et al., 2018)

### 5.7.6 Positive Impact on Breeding Efficiency and Reproductive Management:

Accurate oestrus detection through activity monitoring, as facilitated by satellite connected tags, has the potential to significantly improves the success rates of artificial insemination (AI) and other assisted breeding technologies (Uden, 2025). Furthermore, the collection of individual animal performance data through EID-linked tags allows producers to make more informed breeding and selection decisions, accelerating genetic gain within their herds. McNicol et al reported Precision Livestock Farming (PLF) systems, incorporating fertility sensors, have demonstrated the capacity to increase the number of calves born (4%) and successfully reared (3%) (McNicol, et al., 2024).

## 5.8 Quantifiable Benefits and Favourable Benefit-Cost Ratios (BCR):

The economic viability of adopting satellite enabled smart tag technologies is clear. Trotter et al projected significant benefits for the beef industry, estimating total accumulated benefits between $280 million (minimum) and $808 million (maximum) over a 10-year period, contingent on affordable sensor costs (Trotter, et al., 2018). The report highlighted Benefit-Cost Ratios (BCRs) of 1.1 at a sensor cost of $50/year, increasing dramatically to 5.3 with a sensor cost of $10/year. Note these figures are 2018 figures and would be 20% higher in today’s dollars.

A $15 Total Cost of Ownership is possible with a tag price of $40 amortised over the 5 years ($8 per year) and  assuming an annual connectivity and platform price of $7.There is an expectation of falling costs over time which will firmly position this technology within the high BCR category, ensuring that the substantial benefits identified are economically attractive for producers to pursue.

Additional research and experience in the field since 2018 further support many of the benefit identified by Trotter et al, some of these are identified below. The following tables, adapted from the 2018 report summarise the evolution and quantification of these benefits:

**Table 6 Evolution of Livestock Tag Benefits**

| **Benefit Identified by Trotter et al** (Trotter, et al., 2018). | **Current Status/Statistics (Post-2018)** | **Significant Changes/Trends** |
|---|---|---|
| Improved Grazing Management | GPS tracking optimises pasture use; rotational grazing increases forage mass by ~30%; stocking rates can improve by 5-15%. | Shift from potential to demonstrated improvements in pasture utilisation and stocking rates through GPS and PLF. |
| Enhanced Animal Health and Welfare | Early disease detection up to 7 in the cattle before symptoms; estrus detection accuracy up to 100%; reduced antibiotic use and veterinary costs reported. | Significant advancements in early disease prediction and reproductive management through sophisticated sensors and AI analysis. |
| Increased Biosecurity | USDA mandates EID tags for interstate movement; EID reduces disease investigation time from in the livestock business to hours. | Strong regulatory push towards electronic identification for enhanced traceability and biosecurity. |
| Reduced Mustering Costs | Labour cost reductions of 25% reported with GPS tracking; automation reduces manual Labour needs. | Quantifiable data on Labour and cost savings achieved through GPS and automated monitoring systems. |
| Other Potential Benefits (e.g., genetic matching) | EID aids in genetic improvement through individual performance tracking 1; PLF fertility sensors increase calves born and reared. | Broader applications beyond basic management are being realis<br>ed, with a focus on reproductive efficiency and genetic improvement. |

**Table 7 Quantifiable Benefits of Livestock Tags**

| **Benefit Category** | **Specific Metric/Outcome** | **Quantifiable Data/Statistics (with Source)** |
|---|---|---|
| Grazing Management | Increase in forage mass with rotational grazing | ~30% |
| Grazing Management | Potential stocking rate improvement | 5-15% |
| Animal Health | Estrus detection accuracy | 90% with up to 100% accuracy |
| Animal Health | Early disease detection | Up to 7 days before symptoms |
| Biosecurity | Reduction in disease investigation time | Days/weeks to minutes/hours |
| Labour Costs | Reduction in Labour costs with GPS tracking | Up to 25% |

# 6. Future research and recommendations

Building on the demonstrated technical feasibility of low cost direct to satellite connectivity, the next phase should focus on large, commercial scale deployments with producers to validate performance, cost, and impact under real operating conditions. These deployments should prioritise diverse geographies and production systems—particularly those with lower satellite elevation angles and complex environments—to stress test energy harvesting, antenna performance, and end to end reliability at scale. A consortium model is recommended, engaging leading producers, tag and sensor manufacturers, platform providers and researchers. Commercial scale rollouts will generate the longitudinal datasets necessary to refine device power management, improve firmware stability, and harden hardware for multiyear field life while simultaneously establishing realistic total cost of ownership benchmarks for whole herd adoption.

In parallel, a staged, realistic data integration and AI program should be embedded within these commercial deployments, evolving from foundational data plumbing to advanced decision support only as data depth, quality, and coverage improve. In the initial phase, the focus should be on robust data ingestion pipelines from eSAT enabled tags and on farm sensors into secure cloud environments, standardising schemas, metadata, and time sync across sources such as location, behaviour, environmental, and water infrastructure data. With reliable pipelines in place, the second phase should emphasise descriptive and diagnostic analytics (dashboards, alerting, anomaly detection) that deliver immediate operational value—e.g., geofence breach alerts, water level exceptions, and energy status visibility for tags—to build producer confidence and refine data quality controls in production.

Once sufficient volume and continuity of labelled outcomes exist the program should progress to predictive and prescriptive AI. Priority use cases should be developed with producers but could include things such as early illness risk flags from activity and movement patterns, oestrus detection under varying management conditions, and triage of mustering routes or yarding timing based on animal distribution and terrain etc.

Where practical, lightweight edge analytics on tag or at the gateway can be explored to compress transmissions, trigger event based reporting, and reduce energy consumption, recognising that such capabilities will mature as silicon, firmware, and energy budgets improve. The overarching principle is to keep AI ambitions tightly coupled to data readiness and commercial utility, ensuring that algorithms enhance—not complicate—daily decision making for producers.

By anchoring AI ambitions to real world data maturity and tying R&D tightly to commercial scale deployments, the industry can derisk adoption while compounding value over time. This approach ensures that satellite enabled IoT does more than prove technical feasibility—it becomes a dependable, economical, and widely used foundation for data driven livestock management. With continued investment in large producer cohorts, disciplined data integration, and practical, producer centric decision support, the red meat industry is positioned to unlock sustained productivity gains, stronger biosecurity and traceability, improved animal outcomes, and measurable returns on digital infrastructure at national scale.

## 6.1 Commercialisation Strategy

eSAT Global's commercialisation strategy is pragmatic and collaborative, aiming to embed its technology broadly within the AgTech ecosystem and beyond. A key element is working closely with

AgTech equipment manufacturers, enabling them to integrate eSAT modules into their existing and future product lines. The primary business model involves selling eSAT modules, which incorporate the proprietary SoC, to these solution providers. Additionally, licensing the chipset technology for high-volume applications is a potential avenue, where eSAT would receive royalties.

Smart Livestock Tags have been identified for immediate commercial focus. Building on the successful integration with Smart Paddock tags during this project, eSAT is working directly with Smart Paddock and is engaged in discussions with a range of other smart tag providers to incorporate its communication module.

## 6.2 Broader Applications

The versatility of the eSAT communication technology extends far beyond livestock management, opening a wide spectrum of potential applications across various industries. This market diversification is crucial for achieving the economies of scale necessary for ultra-low-cost chip production and service delivery, benefiting all end-users.

- **Other Agriculture Applications:** The technology is well-suited for a range of on-farm monitoring and control systems, including connected rain gauges, automated water management systems (monitoring levels and flow, controlling actuators), vehicle and asset tracking, gate and fence monitoring, comprehensive weather station reporting, sap flow monitors for horticulture, and instruments for sustainability measurement (e.g., soil carbon levels, air quality).

  Worker health and safety can be improved with personal trackers with SOS capabilities. These could also include fall detection and edge computing reporting on absence of movement.

  There are applications in bushfire prediction and detection and flood resilience tools (monitoring river levels and infrastructure integrity). The system can also support tracking of livestock off farm during transport, enhancing traceability and animal welfare. Tracking of finished red meat products to support "Farm-to-Plate" initiatives.

- **Non-Ag Sector Applications**: Beyond the applications already mentioned, low-data satellite IoT has a wide range of non-Ag Sector uses, particularly where terrestrial networks are unavailable or unreliable, and power consumption needs to be minimal.

The following is a non-exhaustive list of potential non-Ag sector use cases:

1. **Environmental and Climate Monitoring:**
    - **Forest Fire Detection:** Deploying low-cost temperature and smoke sensors in remote forests to provide early warnings of wildfires, enabling faster response times.
    - **Water Resource Management:** Monitoring water levels in remote rivers, reservoirs, and boreholes to aid in flood prediction, drought management, and sustainable water usage.
    - **Air Quality Monitoring:** Tracking pollutants or specific gases in remote industrial areas or ecologically sensitive zones.

- **Seismic Activity:** Deploying inexpensive seismic sensors in remote, geologically active areas to transmit data for earthquake prediction and study.

2. **Remote Infrastructure Monitoring:**
    - **Pipeline Integrity:** Monitoring pressure, flow, and leak detection in remote oil, gas, and water pipelines, preventing environmental disasters and ensuring operational efficiency.
    - **Bridge and Dam Structural Health:** Sensors on critical infrastructure in isolated areas to detect subtle movements, vibrations, or material degradation, providing early warnings of potential issues.
    - **Railway Track Monitoring**: Tracking rail temperature, vibrations, or track integrity in remote sections to prevent derailments and optimise maintenance.
3. **Logistics and Supply Chain** (Specialised):
    - **High-Value Asset Tracking:** Monitoring the location and status of expensive mobile assets like construction equipment, mining machinery, or intermodal containers that frequently operate or travel through areas without cellular coverage.
    - **Refrigerated Cargo Monitoring:** Ensuring temperature and humidity compliance for sensitive goods (e.g., pharmaceuticals, perishable foods) during long-haul transit in remote regions.
4. **Energy Sector (Beyond Grid Safety):**
    - **Remote Oil & Gas Wellhead Monitoring**: Transmitting critical data like pressure, flow rates, and equipment status from isolated well sites, reducing the need for costly manual inspections.
    - **Renewable Energy Sites:** Monitoring the performance and health of remote solar farms or wind turbines, including power output, component temperatures, and security.
5. **Scientific Research and Exploration:**
    - **Oceanographic Buoys:** Transmitting data from buoys used to monitor ocean currents, sea temperatures, salinity, and weather conditions in vast, remote ocean expanses.
    - **Wildlife Tracking (General):** Beyond endangered species, tracking the migration patterns, habitat use, and behaviour of various animal populations for ecological studies.
    - **Glacial Movement:** Monitoring the subtle movements and melt rates of glaciers and ice caps as indicators of climate change.

Take-up in these sectors will benefit the red meat industry as larger volumes of product sales will lead into economies of scale and lower product and connectivity cost.

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