Wildlife Research 2019, **46**(2), 145-153.
doi:10.1071/WR17147_AC

Supplementary material

Aerial VHF tracking of wildlife using an unmanned aerial vehicle (UAV): comparing efficiency of yellow-eyed penguin (Megadyptes antipodes) nest location methods

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Calibration testing

Whereas accuracy is the smallest distance which can be resolved, detection distance is the maximum range where a signal can be detected. Maximum range is more relevant if the main focus is on locating animals (particularly those which may have dispersed widely), as opposed to determining their location as accurately as possible. A wider separation between flight lines can take advantage of detection distance, but may reduce accuracy.

UAV calibration flights were conducted to determine detection distance in the experimental environment by measuring signal strength at known distances. Transmitters of different types (single-stage and two-stage) were placed at measured distances perpendicular to the flight path, and were taped to a 1.5 kg bottle of water lying on its side to approximate the antenna orientation and transmission characteristics on a nesting penguin.

All transmitters operated on individual frequencies in 160-161 MHz bandwidths, with a separation of >20 KHz between frequencies to avoid interference with other tags.
UAV calibration data were collected at constant altitude (30, 50, or 100 m), with transmitters placed at measured distances perpendicular to the flight path (from 0 m up to 500 m), (Figure S1). One transmitter of each type was placed at each distance. The UAV flew along the flight path then turned 180 degrees and returned along the same path, collecting a double peak of signal-strength data from each transmitter, and allowing comparison of signal strength vs range for the different transmitter configurations trialled. (N.B. Depending on the distance between the transmitter line and the turning point, some of the peaks were closer together than others). The UAV's altitude was sometimes changed for the return pass to measure detection ability at two different altitudes during the same flight.

Calibration data showed that signal strength detected at the receiver varied for the different transmitter configurations tested, depending on their output power and antenna type. Two-stage transmitters had the greatest signal strength, and could be reliably detected from 250 m, and in some cases up to 500 m away (the largest distance which was tested) (Figure S4).

If the priority of a search was to detect a signal (rather than maximising position accuracy) this would allow a separation distance of up to 1000 m between flight paths when using two-stage transmitters. Lower-power single-stage transmitters could be detected up to 75 m away (Figure S2 and Figure S3), offering a useful tracking option for smaller animals, or where minimising transmitter size, weight, or hydrodynamic drag is important.

Testing was carried out under real-world conditions at the research site so these calibration data were subject to the effects of topography and vegetation, and therefore provide a measure of detection range using these specific transmitters at this particular site. Consequently, due to the uneven ground and thick scrub these results may be an under-estimate compared to what may be achievable under ideal conditions such as flat open ground, or with better transmission characteristics such as transmitters located higher off the ground and with a vertical transmission antenna orientation.

In addition, changing the detection antenna altitude can alter the “footprint” of coverage seen by the receiver, therefore affecting detection ability. It was evident from the testing that at the maximum 500 m range of a two-stage signal was detected at the higher altitude of 100 m, but not at the lower altitude of 50 m. This illustrates the complex interaction of factors which can affect detection range. It is therefore advantageous to conduct range testing according to the specific field conditions which will be encountered.

Signal strength affects the detection range of a particular transmitter type in a given set of conditions, with implications for choosing transmitter type, as well as planning flight paths and flight line separation distances. Due to the variability in detected signal strength for different types of transmitters (based on their output power, antenna configuration, as well as different environmental conditions including vegetation and topography), different transmission antenna combinations may be affected in different ways. Calibration tests are also useful when determining an optimum flight path separation and altitude for surveys.

A useable VHF signal strength could be detected by the Drone Ranger system within ± 3 KHz of the peak transmitter frequency. Transmitters can sometimes drift up to 3-5 KHz from their manufactured frequency, highlighting the usefulness of tuning the receiver to scan for peak transmitter signal outputs as well.

Signal detection

Flight path separation and/or height can be modified depending whether the focus is for a larger scale search (eg. locating the signal from a missing transmitter or a widely-dispersing animal), or whether finer scale positioning is required. A wider flight line spacing increases the search area covered thereby increasing the chance of detecting a transmitter during a flight, but decreasing the precision when estimating signal origin.

Successful VHF tracking depends primarily on the signal strength detected by the receiver, which is affected by range. Signal strength decreases with increasing distance from the transmitter according to the inverse-square law, where the signal strength is reduced by 75% when distance from the source is doubled (Kenward 2001).

The most variable factor affecting signal strength and therefore the most likely to affect successful VHF tracking in the field are the effects of terrain and vegetation which can attenuate or reflect the signal, making it difficult to detect and track (Kenward 2001). Ridges, gullies, cliffs, and thick vegetation can all reduce detection range. Additionally, moisture on vegetation can also reduce detection range.

Increasing altitude can overcome the effects of terrain or vegetation on VHF detection. A higher receiving antenna automatically has a wider field of view, and the signal from the transmitter is less likely to be screened by ridges or gullies (Seddon and Maloney 2004). When tracking from the ground a signal may have to travel the entire distance to a ground-based receiver through vegetation, whereas an aerial receiver can fly above the forest canopy (which is a maximum of a few metres high in the subantarctic), thereby reducing effects of terrain and vegetation.

Signal strength can be affected by a number of other factors including the power output of the transmitter and its antenna size, type, and orientation (Kenward 2001). The type of transmission antenna may be influenced by expected animal behaviour. Considerations may include the likelihood of antenna damage, whether tracking underground is needed, or whether there is a chance of it getting entangled in vegetation or other obstacles. Shorter antennas (including internal loop antennas) will generally have a reduced transmission range compared to a longer whip antenna, but may be less prone to damage or becoming entangled. Detection range can also vary due to an animal's posture, or if it moves into different environments.

Search methods

The efficiency of an aerial search method is governed by the area which can be searched at a time (based on the detection range), the total size of the area to be searched, and the speed at which a search can be conducted. UAV-based systems have been described which utilise a single-channel VHF receiver (Cliff *et al.* 2015; VonEhr *et al.* 2016). A single-channel receiver determines the approximate location of the transmitter using triangulation. Triangulation of multiple transmitters requires frequencies to be scanned sequentially so becomes progressively less efficient as more transmitters are tracked. Tracking 50 transmitters requires over 5 minutes per scan, and a minimum of three scans is needed to triangulate a bearing to each target location, requiring a total search time of 15 minutes or more. This is approaching the maximum battery life for a small UAV so restricts searching to a single triangulation per flight. However, a single triangulation can only cover a search area equivalent to the detection range. Based on the observed maximum detection range of small single-stage transmitters of 75 m in this environment, a single triangulation would not provide coverage of the whole penguin nesting area. Depending on the location of transmitters within the landscape it could take up to 26 scans to cover each 500 x 300 m breeding area. Based on these efficiency estimates we developed a multi-channel receiver capable of scanning 50 frequencies simultaneously, while the UAV maintains cruising speed.

A hovering UAV has been shown to generate more disturbance than one passing overhead (Mulero-Pázmány *et al.* 2017). Therefore, hovering in place for up to 5 minutes at a time as required for triangulation has the potential to create significantly more disturbance than a dynamic search. Yellow-eyed penguin nests are separated by at least 20 m from each other, therefore with a separation of 30 m between flight lines the odds of directly overflying a nest are low. If needed, the separation distance can be increased to reduce the likelihood of disturbance from direct overflights still further. If a dynamic search does happen to directly overfly a nest, the speed the UAV is travelling would limit the exposure to any disturbance to a few seconds.

Comparison with other electronic tracking methods

Aerial VHF tracking has a number of advantages over other common electronic tracking methods. Unlike GPS receivers or satellite transmitters (such as Argos) which require a clear view of the sky, VHF transmitters can be used under forest canopy, underground, or even inside buildings (although the detection range may be reduced).

VHF transmitters are often smaller than GPS tags. At the time of writing, VHF transmitters are available as small as 0.19g in weight (Biotrack, UK) and can therefore be attached to much smaller animals than is possible with GPS or satellite tags. VHF transmitters are usually cheaper than many other electronic tracking devices designed for use on wildlife, and unlike GPS tags this technology also does not require any separate form of remote download from the tag, or the recovery of the tag in order to retrieve position data. In this situation using VHF tracking is much quicker than using GPS as GPS tags utilising satellite download have an inherent delay, since satellite uploads of position data usually only occur daily (or less frequently where cost or battery life is limiting). Deploying GPS store-onboard tags would also have involved a minimum delay of several days before electronics could be retrieved to download the data.

In addition, GPS and satellite technologies both have higher power requirements which limits battery life and the total number of possible position fixes, and performance is worse in environments where view of the sky is limited. As a result GPS tags often have a larger battery to compensate, thereby increasing tag size and weight compared to VHF transmitters. To maximise battery life, GPS tags are usually limited to a number of preset GPS fix attempts (pre-programmed at set times of the day based on battery life predictions). However, any failed fixes will use up additional power, so the actual number of fixes that can be recorded will be governed by the terrain and animal behaviour when deployed.

VHF tracking also has a number of advantages over satellite positioning systems (e.g. Argos) since VHF transmitters are smaller, cheaper, and more accurate. Satellite transmitters require a clear view of the sky, and position accuracy can range from +/- 100 m to over a kilometre. Satellite transmitters must transmit continuously, but position data can only be calculated while a satellite passes overhead, restricting the number of positions which can be calculated in a day. To limit data charges and/or battery life, satellite transmitters are often duty-cycled to only transmit during part of the day, meaning no positions can be received outside this time.

Rather than being limited to a finite number of fix attempts, or positions only at certain times of the day, VHF tags transmit continuously while they are on so aerial VHF tracking using the Drone Ranger system could be used to provide positions at any time, or even continuously.

Future uses

We were able to use a GIS to determine the location of nests with a reasonable degree of accuracy, simply by looking at a spatial plot of the signal strength values collected. If a quantitative output and/or greater precision is required an algorithm could be incorporated to calculate a probability surface of the signal strength data, perhaps by using triangulation and/or performing a 'weighted' kernel density analysis. This has the potential to provide greater accuracy than a basic analysis of maximum signal strength since the strongest signal may not necessarily be detected at the closest distance to the target. Doppler shift and/or any slight delays in signal processing could be accounted for to improve accuracy still further.

In addition to locating nests, aerial VHF tracking could also be used to monitor wildlife. Daily flights were useful to determine which penguins were on their nests, and which were away at sea foraging. Comparing location over several flights would also assist with determining whether penguins were on a nest or just loafing in the area, without needing a visit by a ground team. Nesting birds would be expected to be consistently in the same location, whereas loafing birds would be expected to move around over time. Penguin breeding areas were approximately

150,000 m^3, or 300m x 500m. With a maximum range of 3 km per battery, an area this size could be searched on one battery with a separation of 50 m between flight lines. With a closer spacing, or in stronger winds this might require two batteries to cover the whole area at once. Depending on project requirements, different UAV platforms could be utilised to increase range, flight time, and payload capacity, and allow operation in a wider range of weather conditions. A camera could also be fitted to assist with monitoring wildlife in the field.

UAVs using a variety of different sensors have proven useful for a wide range of monitoring techniques including estimating body condition (Christiansen *et al.* 2016) and abundance of animals (Goebel *et al.* 2015), and for mapping habitat (Koh and Wich 2012). The addition of VHF tracking could improve efficiency and provide comprehensive monitoring techniques for the future.

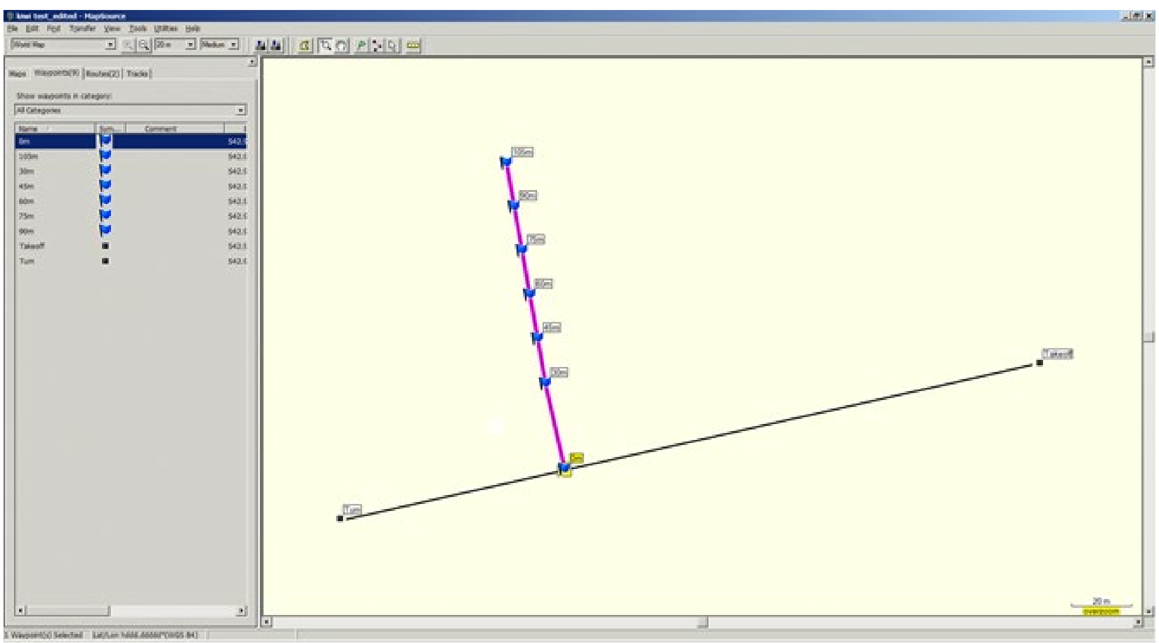

Fig. S1. Example calibration flight path to map signal strengths (from Takeoff point to Turn point, and return to Takeoff point) showing the placement of transmitters at measured distances, perpendicular to the flight path. This was also used to test high-density transmitter detection.

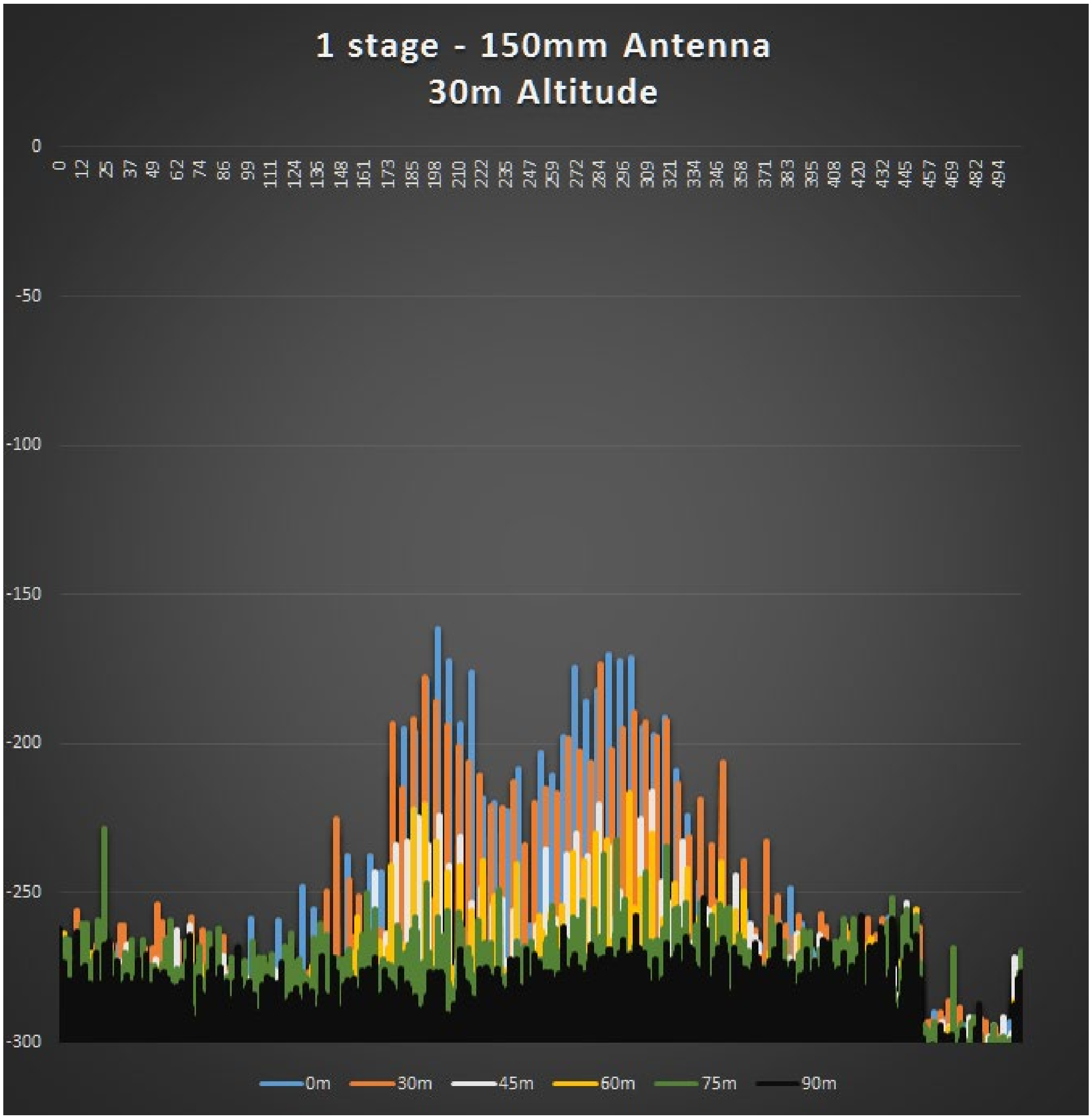

Fig. S2. Signal strength plot (-dB) vs Time (s): Single-stage transmitter with 150 mm whip antenna at 30 m altitude – signal detected up to 75 m away (green).

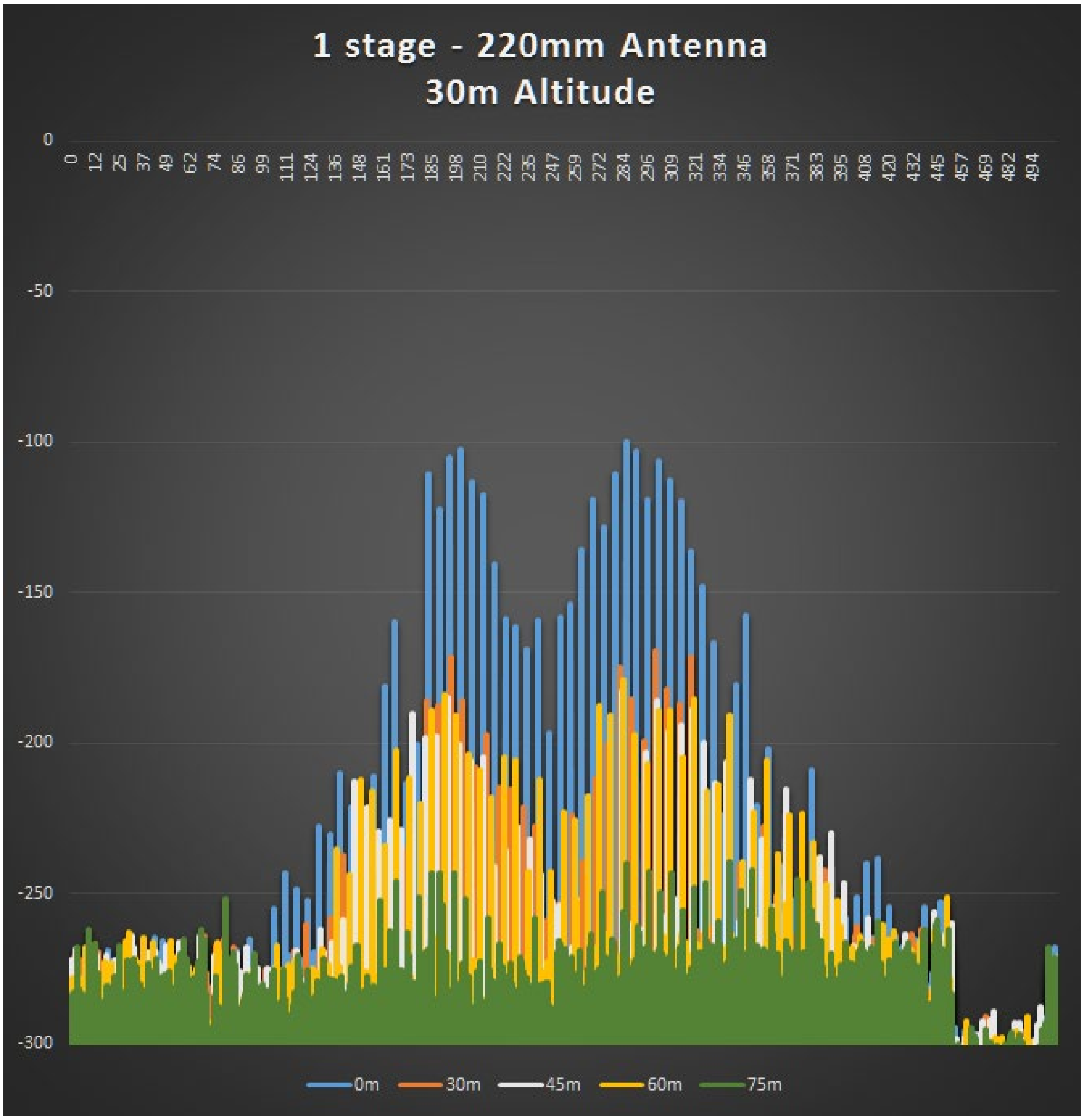

Fig. S3. Signal strength plot (-dB) vs Time (s): Single-stage transmitter with 220 mm whip antenna at 30 m altitude – signal detected up to 75 m away (green).

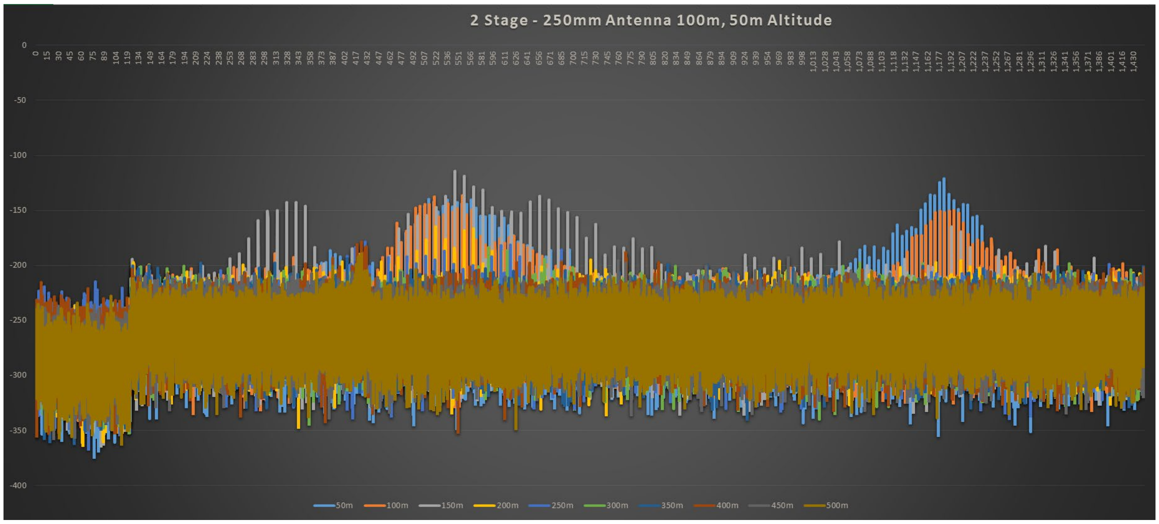

Fig. S4. Signal strength plot (-dB) vs Time (s): Two-stage transmitter with 250 mm whip antenna at 100 and 50 m altitude (recorded during separate passes in the same flight) – signal detected at least 500 m away at 100 m altitude (olive) only.

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