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Performance Analysis of a Wildlife Tracking CubeSat Mission Extension to Drones and Stratospheric Vehicles

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Abstract: This study presents a performance analysis for an Internet-of-Things wildlife radio-tracking mission using drones, satellites and stratospheric platforms for data relay with Spread Spectrum Modulation devices. The performance analysis is presented with link and data budgets, calculations of the area coverage, an estimation of the time resolution and allowable data amount of each collar, a power and energy budget and consequent battery pack and collar weight estimations, cost budgets, and considerations on synergetic approaches to incorporate more mission segments together. The paper results are detailed with example species to target with each collar weight range, and with design drivers and guidelines to implement improved mission segments.

Keywords: CubeSat; stratosphere; drone; UAV; wildlife tracking; human–wildlife conflict; satellite; radio; tracking

Citation: Marzioli, P.; Garofalo, R.; Frezza, L.; Nyawade, A.; Santilli, G.; JahJah, M.; Santoni, F.; Piergentili, F. Performance Analysis of a Wildlife Tracking CubeSat Mission Extension to Drones and Stratospheric Vehicles. *Drones* **2024**, *8*, 129. https://doi.org/10.3390/drones8040129

Academic Editors: Kate Brandis and Roxane Francis

Received: 11 July 2023
Revised: 22 March 2024
Accepted: 26 March 2024
Published: 29 March 2024

1. Introduction

In recent years, the need for more thorough wildlife tracking and management [1], with a focus on the growing urbanization [2,3], agricultural advancement [4–9] and deforestation [10] of countries hosting richer biodiversity and a wider variety of animal species, has met the opportunities provided by rising technologies such as remote sensing, artificial intelligence, satellite navigation and tracking.

Animal tracking technologies are in general relying on a multiplicity of engineering disciplines to carry out feasible and affordable methods for monitoring and tracing animals. Wildlife radio-tracking has been developed since the 1960s with simple methods retrieved from standard aeronautics and space methodologies and techniques. As an example, radio-tracking was at first performed with direction tracking [11], as per elder aircraft radio-navigation techniques. The transition to a broader utilization of GNSS (Global Navigation Satellite Systems) chips within collars has been progressively improved since the 1990s [12,13], allowing for better tracking of far-ranging species and for resolution improvement in the collected data [14].

UAV-based tracking for wildlife [15,16] is usually based on optical or radar-based monitoring techniques [17–22]. However, an evolution from "traditional" hand-held radio-tracking methodologies to drone-based radio-tracking [14] can significantly increase the capacity and performance of these tracking methods and they are under testing. In general, autonomous wildlife radio-tracking can save manpower, adopt more comprehensive approaches and improve accuracy and precision in tracking, justifying the generally higher costs of implementation of such systems with respect to hand-held devices.

Novel technologies such as Internet-of-Things [23] and Software Defined Radios have in the recent years started to be applied to wildlife radio-tracking, by re-adapting old concepts to new, miniaturized technologies [16], and by implementing innovative technologies within new mission scenarios for fauna tracking and wildlife monitoring [24]. Such implementation is driven by the mass and volume reduction in all systems, by their autonomy and performance increase due to the increase in available computing power of small chips, and finally by the enormous reduction in costs related to the production and deployment of microcontrollers, chips, sensors and communication modules. In this framework, the reduction in dependability on other systems (with particular regards to communication systems) uncovers interesting perspectives, as IoT protocols are often open and easy to apply to open-access and programmable devices for communication.

In this perspective, the last years of research have shown how innovative communication systems and Radio-Frequency (RF) systems have been applied to new mission envelopes for aircraft and spacecraft. In particular, the utilization of Spread Spectrum (SS) and Internet-of-Things (IoT) technologies, such as Long Range (LoRa) transmitters, for satellite-based instrumentation tracking has been investigated with multiple demonstrator missions [25], such as KITSUNE [26,27], with the implementation of TinyGS networks [28]. The same technologies have been adapted for experimentation on-board a nano-satellite for monitoring wildlife in Kenya.

Kenya presents a remarkable heritage of biodiversity and a certain dependency of the national economy on wildlife tourism despite a dramatic decrease in wildlife species and exemplars, with a high number of endangered species and with many at risk of extinction [29,30]. Such wildlife decrease and the extinction risk increase is occurring mostly outside the boundaries of the National Parks [31]. Further threats to wildlife are imposed by so-called human–wildlife conflicts (HWCs), which can easily lead to damage, casualties and animal death [32–36]. With the new threats to wildlife and biodiversity and with a substantial dependency of the country on the income generated by National Parks, Kenya needs a thorough tracking method for wildlife.

The usage of wildlife tracking innovative technologies can be focused towards multiple objectives, including the prediction of HWC and the prevention of such events when wildlife gets closer to the National Parks' boundaries; the collection of data related to migrants and non-migrants and their analysis for migrant path prediction; the evaluation of nourishment, ecosystem health and climate change effects and adaption of the different species; the preservation of endangered wildlife exemplars; and even the prediction of the transmission and circulation of diseases potentially transmissible to humans. Aircraft or spacecraft wildlife tracking can contribute significantly to solving the problems associated with wildlife preservation in the African nation, while allowing the gathering of, in the spacecraft case, information about migrant exemplars throughout the year, and not only during their passages within the National Parks' boundaries.

This work will present a performance analysis and feasibility study of a Spread Spectrum Modulation (SSM)-based wildlife radio-tracking method assisted by satellite, stratospheric and UAV platforms. The design of the space and ground segments will be based on the lessons learned by WildTrackCube-SIMBA, a 1U CubeSat mission launched in 2021 by Sapienza University of Rome, the University of Nairobi and Machakos University, and supported by the Italian Space Agency (ASI), the Kenya Space Agency (KSA), GK Launch Services and the International Astronautical Federation (IAF). The satellite is primarily aimed at demonstrating the opportunities created by IoT technologies for CubeSat-based tracking of wildlife in the National Parks of Kenya. The satellite equips multiple software- and hardware-based receivers aimed at data relay with ground-based animal tags and collars. The spacecraft was launched in March 2021 and it has concluded the hardware technology demonstration phase to verify the communication functionalities with the ground, their compatibility with a very small satellite platform and the optimization phase of the communication methods to be used. The current project phase includes the potential extension to drone and stratospheric airship tracking for completing and expanding the depth and detail of the transmissible data, and of the designed IoT technologies communication method capacity.

This paper will present the features of the designed data communication system for wildlife tracking in Kenya and the performance analyses in terms of the link budget calculation, data rate estimation, area coverage calculation, power and energy consumption analysis and cost considerations of a multi-segment radio-tracking mission for wildlife monitoring in Kenya. The paper's main contributions are to provide guidelines and figures of merit for the establishment of autonomous radio-tracking devices when considering full autonomy (i.e., independence from cellular networks, satellite phone services, etc.) and the implementation of IoT and SDR technologies. This paper is written from a system engineering perspective and arrives to the determination of the concept of operations for synergetic approaches to different in-flight mission segments involving UAVs, by referencing findings from the monitoring of mammals in the National Parks of Kenya.

2. Internet-of-Things Tracking through Spread Spectrum Modulation Chips

Internet-of-Things (IoT) wildlife tracking is based on in situ monitoring of wildlife. The working principle relies on in situ chips (typically wildlife collars) equipped with low-cost, low-power transmitters that are able to perform data relay with fixed ground stations or vehicles. Approaches to IoT chip implementation for radio-tracking can be directed towards direction finding [37], RSSI tracking [38], Time Difference of Arrival (TDOA) [39], or GNSS-based tracking. Communication to the monitoring segment can be realized with the support of GSM/LTE cellular networks [24]. In general, independent systems can reduce their level of dependability by implementing independent platforms and not taking advantage of cellular networks and other commercial communication systems, as will be presented in this paper. Furthermore, the conducted approach (IoT chips transmitting their positions) does not require the in-flight platforms to actively play any roles in the position determination, such as in radio direction-finding, TDOA-based approaches or when stating signal power and RSSI. In this case, the in-flight vehicle only needs to receive the IoT packets to successfully identify and locate the animal, without any further steps to be taken.

This paper will focus on LoRa (Long Range) IoT hardware for wildlife monitoring, in compliance with the technology demonstration operated by the WildTrackCube-SIMBA CubeSat, which will be used as the case study for the space segment. LoRa is a Spread Spectrum Modulation (SSM) communication method, which allows for several tuning parameters to optimize the communication link. LoRa in general allows for the implementation of miniaturized transceivers and minimized transmission power with relatively low data rates (in the range of hundreds or thousands of bits-per-second). The effort toward hardware miniaturization and used power reduction suggests an exploitation of such technology for wildlife monitoring, where the collars' operational lifetime should be maximized at all costs to avoid too frequent interactions with wildlife. The main parameters to be set on the LoRa communication are as follows:

- The bandwidth, which will define the maximum allowable data rate;
- The Spreading Factor (SF), which helps in defining the chirps (or symbol) rate within LoRa. To a lower SF is associated a faster chirp rate and a faster transmission of data, while to a higher SF corresponds a lower distortion at low power (and high distance) with a lower data rate;
- The Coding Rate (CR), which represents the proportionality of the informative bits over the total number of transmitted bits. The LoRa transmission usually happens by implementing redundant the informational bits transmission. As an example, if the CR is 4/8, the same information of 4 bits is transmitted twice.

The main performance parameter to define the communication well functioning is the C/N or signal-to-noise ratio (SNR) figure. While for Spread Spectrum modulation systems the figure is often used as the margin-over-sensitivity parameter, the usage of Software Defined Radios, which help in adding flexibility to the communication parameters and features, imposes to only evaluate positive SNR. This constraint is imposed by the design of the mission used as the case study, where the usage of SDR hardware was a requirement to keep a certain flexibility in the technology demonstration and to assure perfect functionalities in-orbit. These tuning and performance parameters will be discussed for all mission segments when designing the link for optimizing the wildlife tracking method performances.

3. Mission Segments

The following subparagraphs will describe the designed mission segments. The ground and space segments use the implementation of the WildTrackCube-SIMBA mission as the case study. The lessons learned from the experimentation on the space mission segments will be used for determining the features of the two new segments, i.e., the stratospheric and drone segments.

3.1. Ground Segment: Wildlife Collars

The wildlife collars were prototyped with general purpose electronics in order to acquire the following data:

- Wildlife positioning, through GNSS (Global Navigation Satellite Systems) receivers;
- Inertial Measurement Units (IMUs), able to propagate the animal position and to support the GNSS module;
- Temperature and humidity, through miniaturized sensors, in order to acquire the animal's body temperature and to verify the environmental conditions;
- Heart rate (implemented as an optional functionality); such sensors can provide a deeper insight over the exemplar's health status and habits;
- Housekeeping, with data on the general health check of the electronics involved in the collar.

Such sensors shall be accompanied by a Data Handling system, usually equipped through a single chip computer, a Power Storage and Distribution Unit (PSDU), able to provide power through the equipped batteries and to regulate it for all power lines, and a LoRa transmitter to uplink the data to the other mission segments. A picture of the collar prototype is presented in Figure 1.

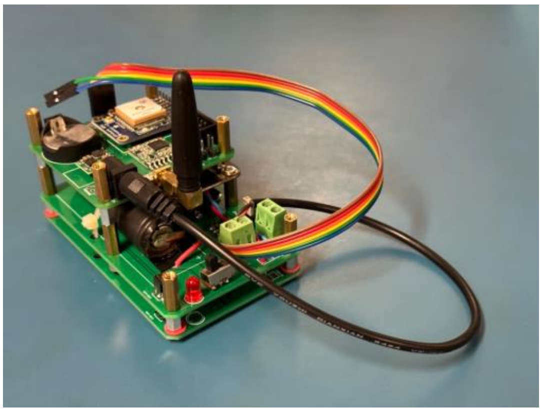

Figure 1. Collar prototype.

A general schematic of the collar connections is presented as a block diagram in Figure 2.

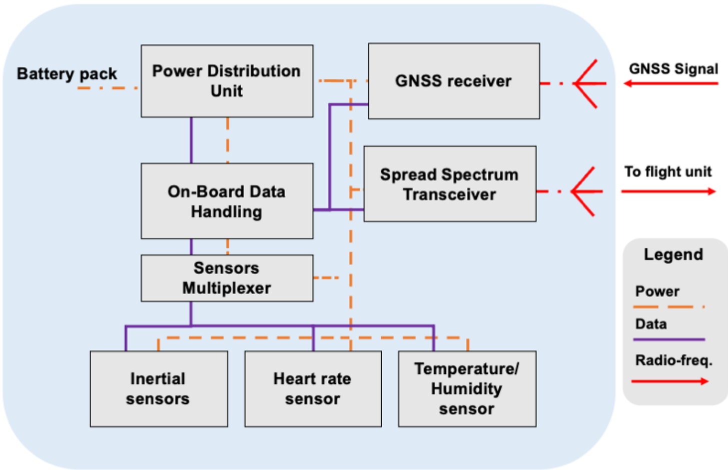

Figure 2. Collar electronics architecture scheme.

3.2. Space Segment: 1U CubeSat Mission Description

WildTrackCube-SIMBA is a 1U CubeSat mission developed by Sapienza University of Rome (S5Lab research group), Machakos University and the University of Nairobi, with the support of ASI and KSA and with the launch opportunity on-board a Soyuz 2.1a launch vehicle offered by Gk Launch Services and the IAF. The spacecraft had, as main payload, multiple software- and hardware-defined receivers for IoT, Spread Spectrum communication from the ground. The main mission objective is to demonstrate the in-orbit capabilities of IoT communication systems for wildlife tracking in the National Parks of Kenya, in order to precisely track, monitor and manage the different species population within the different ecosystems of the target African nation. The satellite is depicted in Figure 3.

Figure 3. WildTrackCube-SIMBA satellite.

The satellite was launched on 21 March 2021 from the Baikonur Cosmodrome in Kazakhstan to a 500 km high, sun-synchronous orbit with an approximate LTAN (Local Time of Ascending Node) at 11.00 a.m.

The main technology used by SIMBA relies on a Spread Spectrum radio receiver at different bands from portable, lightweight, low-power consuming animal collars. Within the first two years of the mission, the communication link had been optimized by testing all the parameters of the Long Range (LoRa) ground-to-space link and the functionalities, design and operations of the ground segment (wildlife collars). The Concept of Operations scheme is reported in Figure 4.

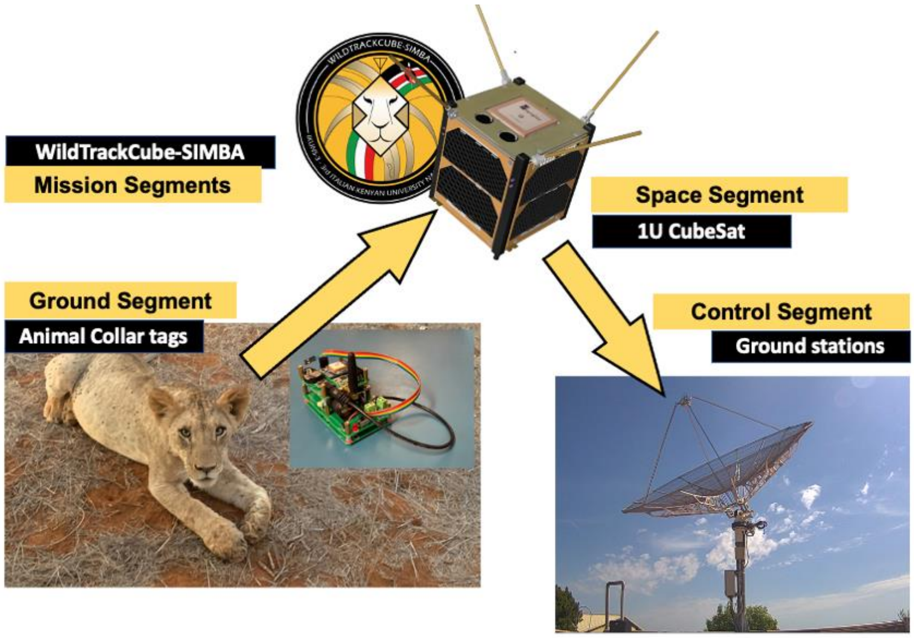

Figure 4. WildTrackCube-SIMBA CubeSat mission concept scheme.

The optimization of the ground-to-space LoRa link provided lessons learned and guidelines for similar operations with CubeSats, including design drivers for a follow-up satellite mission and operational guidelines for an extension to other mission segments, as it will be reported in the next paragraphs.

3.3. Stratospheric Segment: High Altitude Platform Station (HAPS)

The current research and development trend for stratospheric aviation is the demonstration of unmanned stratospheric airships that are able to perform station-keeping at 25–30 km of altitude [40–42]. Such vehicles could provide quasi-satellite Earth observation, monitoring and data relay systems at much lower costs than satellite constellations.

A HAPS could greatly support a wildlife monitoring mission, making available a stable data relay link with station-keeping capabilities and an extended field of view of hundreds of kilometers. The development of a data relay instrument on a HAPS involves a fraction of the total costs of a 1U CubeSat (or a CubeSat-size payload for a larger satellite platform) and the needed time for verification and qualification is indeed much shorter than for spacecraft. The same experimental data relay platform can be deployed on stratospheric (uncontrolled) balloons for on-condition monitoring, providing several hours of operations over the ROI without any station-keeping or vehicle control capabilities.

3.4. Atmospheric Segment: Fixed- or Rotary-Wing Unmanned Air Vehicles

The deployment of UAV (Unmanned Air Vehicle) monitoring devices over the ROI can be very beneficial to a radio-tracking wildlife monitoring mission. The radio-tracking operations required by the mission concept do not impose any requirements over the FOV, GSD (Ground Sampling Distance), field of regard and strict constraints on overflight of the ROI, as data relay can be performed with payloads at relatively low elevation angles. In this work, scenarios and performances for both fixed- and rotary-wing drones will be presented. The reference UAV models are commercial, general purpose, in the cost range of 10–30 thousands of Euros and able to provide a sufficient payload capability (around 0.5 kg) for the operations of the CubeSat-size data relay payload, with minor modifications for atmospheric flight.

4. Performance Analysis

The performance analysis will be addressed to different variables:

- The quality of the established communication link, through the analysis of SSM link budgets and by maximizing the data rate yet keeping the SNR positive (as per the WildTrackCube-SIMBA payload description);
- The available scanned area and time on target, by differentiating with scanning platforms (satellite and fixed-wing UAVs) or hovering platforms (HAPSs and rotary-wing UAVs);
- The available data budget, with a focus on the achievable telemetry data from each collar for every day of operations with the analyzed mission segments;
- The power budget of the collars, as a result of the needed packets transmission rate calculated in the data budget paragraph, which will allow the estimation of the collars' total mass;
- The overall cost of the experimental platforms and operations.

Each sub-paragraph of this section will be dedicated to one of the presented budgets. The development of each budget for the drone segment stand-alone will be included in the main body, together with the summation of the system budgets for all segments. Additional information on the development of satellite and stratospheric budgets will be provided in Appendix A as supplemental data.

4.1. Link Budgets

The link budget calculations take into account the performances of the collar modules described in Section 3.1 and the LoRa receiving SDR payloads to be fitted in all the described vehicles. The link budget tables are provided, for brevity, for the atmospheric (UAV) segment only, before leading to the summation of the achieved results. The architecture of the receiving modules is supposed identical, based on the SDR, and equal to what is equipped on-board the WildTrackCube-SIMBA satellite (described in Section 3.2). It will be visible how with the decrease in the vehicle slant range, it will be possible to increase the data rate with a significant link margin. The development of detailed link budgets for the other segments will be provided in Appendix A.

A high link margin and data rate can be realized through drone platforms. The link budget finds no differences between rotary- and fixed-wing UAVs, but it is detailed for different over-the-ground height values (100 to 2000 m) in order to cover all the operational envelopes of both typologies of aircraft. The drone link budget is reported in Table 1. In order to verify how the margin is sufficient for all elevation angles, the elevation angle is decreased to 5 degrees, further increasing the slant range.

The case study reports that great link margin values (15 dBi and higher) are achieved by setting the communication to the lowest values of SF and the highest supported data rates (with the highest bandwidth settings) from the communication payloads at ground and on-board the drone. As will be visible in the next table, the drone realizes the maximum possible performance (in terms of data budget and bandwidth), realizable by the case study LoRa chips in all considered envelopes. A summary of the achieved performances with the link budgets of the different mission segments is presented in Table 2.

Table 1. Atmospheric segment link budget for different height values.

Cases	**Drone (UAV)—Atmospheric Segment Link Budget (Fixed- and Rotary-Wing)**				
Height [m]	100	200	500	1000	2000
Distance [km] and elevation [degrees]	1.1 (5°)	2.3 (5°)	5.7 (5°)	11.5 (5°)	22.9 (5°)
Spreading Factor			7		
Bandwidth [KHz]			500		
Frequency [MHz]			868		
TX Power [dBm]			17		
Cable Loss [dBm]			2		
TX Antenna Gain [dBi]			1		
		Outputs			
EIRP [dBm]			16.0		
Free Space Path Loss [dB]	92.41	98.44	106.39	112.41	118.44
Nominal Bit Rate [bps]			9114.58		
Link Margin [dB]	+41.1	+35.0	+27.1	+21.1	+15.0

Table 2. Link budget comparison.

	Satellite	**Balloon**	**Drone (Low Altitude)**	**Drone (High Altitude)**
Distance [km]	1000 (30°)	172.8 (10°)	1.1 (5 deg, 100 m altitude)	22.9 (5 deg, 2000 m)
SF	11	7	7	7
Bandwidth	62.5 KHz	125 KHz	500 KHz	500 kHz
Free Space Path Loss [dB]	151.16	135.97	92.41	118.44
Bit Rate (bps)	111.9	2278.65	9114.58	9114.58
Link Margin [dB]	+5.88	+5.56	+41.1	+15.0

From the link budget calculations summary, it must be remarked how the different segments realize different performances, mainly related to the great reduction in slant range from satellite distances (over 1000 km) to drones (from 5 to 25 km). The calculations already suggest how some sort of synergy could greatly improve the data resolution and mission data impact for wildlife monitoring. The area of interest for various segments' monitoring will improve the depth of the analysis results and it will be analyzed in the next paragraph.

4.2. Scanned Area, Typical Flight Time and Time-on-Target

In order to compute the relevant performance values for the area to be covered by each mission segment, it is useful to divide the selected vehicles into two groups:

- **Hovering vehicles**, capable of performing hovering or station-keeping, where the vehicle holds position above the area of interest and targets. This capability belongs to stratospheric airships and rotary-wing drones;

- **Scanning vehicles**, not capable of performing hovering, but are kept flying (or orbiting) and are able to provide data from larger and more dispersed areas. In this category, the space segment and fixed-wing drone are included.

By starting from the hovering vehicles analysis, it can be stated how the stratospheric platform can present relatively long flights (even weeks in station-keeping for each flight), while the high altitude (30 km) of the platform guarantees a visible range of around 170 km (with a slant range of roughly 172 km). The scanned area is therefore 90,704 km^2, with an availability of the link for an entire flight of one to two weeks.

The rotary-wing drone has a much lower autonomy and reachable range than the stratospheric platform. By analyzing the performances of a typical rotary-wing drone with medium–high costs, the flight duration can span between 30 min and 1 h. By considering the lower value (as a conservative value that can also include the flight from and to the airfield), the rotary-wing drone can survey an area of 12 km^2 (lower altitude) to 1000 km^2 (with flights closer to the theoretical ceiling altitude of rotary-wing drones). It must be remarked how the latter value is merely theoretical, while rotary-wing drone operations are in general conducted at a maximum few hundreds of meters of height, without a transition to thousands of meters. Even if theoretical, the scanned area value of this platform is still almost 100 times smaller than any stratospheric platform.

When transitioning to scanning vehicles, the satellite maintains visibility over areas of 1000 km of radius for three minutes only during medium–high elevation (equal or higher than 30 degrees) passes. A satellite in SSO like WildTrackCube-SIMBA is able to scan the entire Earth surface in 7–8 day cycles, but with rarer repetition cycles given the orbit mechanics behind the satellite motion. The satellite is in general able to repeat two or three medium–high elevation passes per week over the same ROI, which can amount even millions of square km. By considering a single 3 min pass, the satellite can receive data from collars in areas spanning around 3,000,000 km^2. Its channel availability will be severely impacted by the low data rate analyzed in the previous section, as will be seen in the next paragraphs.

The fixed-wing UAV can reach lower values of scanned areas given a relatively lower altitude. By considering a total flight time of 90 min, with 5 min per flight dedicated to take off, climb and approach-terminal air operations, each flight gives 85 min of availability at cruise altitude, which spans (as per previous analyses) between 100 and 2000 m. The maximum range reachable by similar platforms stays at around 15 km, therefore the possible scanned area spans between 120 and 650 km^2.

A summary table is presented in Table 3.

Table 3. A summary of the area coverage performance analysis.

Fea	Hovering Platforms			Scanning Platforms			
Segment	**Stratospheric Platform**	**Rotary-Wing UAV**		**Satellite (Longer Timespan)**	**Satellite (Single Pass)**	**Fixed-Wing UAV**	
Altitude	30 km	0.1 km	2 km	550 km		0.1 km	2 km
Max range (ground distance)	170 km	6 km	23 km	1000 km		6 km	23 km
Total area of FOV	90 000 km^2	12 km^2	1000 km^2	Entire Earth surface	3,000,000 km^2	120 km^2	600 km^2
Availability time	1–2 weeks (continuous) for each flight	30–60 min per flight		7–8 days	3 min, 2 passes per day	80–90 min per flight	

It appears evident from this analysis how all the platforms realize different values of coverage over a ROI and how a synergetic approach to these platform operations can be largely beneficial for improving data resolution (with the main focus on the hovering platforms) and coverage (with more impact from the scanning platform) together, largely improving the outcomes of the experimentation.

4.3. Data Budgets

As a result of the previous two sub-paragraphs, it is possible now to proceed with a data budget. By taking into account the information calculated or obtained from the data link quality and from the effective time on target for each platform, it is now possible to interface the mission profiles characteristics with the packet structure and data budget. The paper will consider two possible data structures, including "normal" packets (used during the WildTrackCube-SIMBA mission) of 96 bits and "extended packets" of 208 bits. The normal packet will feature, besides headers and overheads, the GNSS position of the collar and information on temperature and humidity, while the extended packet will add information on the animal's health. Detailed information on the packet structure can be found in Appendix A.2.

The analysis focuses on the deployment of 100 collars for all segments in order to calculate the maximum number of packets theoretically possible to transmit data from each collar for every day of operations. The data budget analysis results are reported in Table 4. The data budget is computed by taking as granted that the collars can store data in buffers to be emptied, and not only gather and transmit the instantaneous telemetry. Such a feature is implemented within the prototyped collars.

Table 4. Data budgets for different mission profiles.

	Satellite (WildTrackCube-SIMBA)	**Stratospheric HAPS**	**Drone (Fixed-Wing, Daily Flight)**	**Drone (Rotary-Wing, Daily Flight)**	**Drone (Rotary-Wing, One Flight per Week)**
Number of collars deployed	100	100	100	100	100
Type of packet and amount of bits per collar packet (bit)	Normal, 96	Extended, 208	Extended, 208	Extended, 208	Extended, 208
Data rate (bps)	111.9	2278.65	9114.58	9114.58	9114.58
Minutes per day in visibility of collars	6	1440	90	60	60
Duty cycle *	80%	80%	80%	80%	80%
Bits per day	32,227	157,499,942	39,374,985	26,249,990	3,749,998
Bytes per day	4028	19,687,493	4,921,873	3,281,248	468,749
Packets per day	336	757,211	189,302	126,201	18,028
Packets per collar per day **	3	7572	1893	1262	180
Time interval for each collar ***	7 h	11 s	46 s	68 s	8 min

Notes: * Out of the time in visibility, 80% of the time is considered as used for the packet transmission to the various platforms. This covers possible commands downlinked from the platforms (if implemented), the redundancy time for some packets transmission and sufficient time for other tasks (such as optical observations for drones or stratospheric airships). ** Calculated as the number of packets that each collar can uplink to the platform per day. In the drone's case, a buffer is considered on-board to be uplinked and emptied at each drone flight. *** Calculated as the minimum interval between each pair of packets in a single day of acquisition.

The table highlights how the different segments realize data budgets with different orders of magnitude of values in terms of transmissible packets per day from each collar.

The atmospheric segment, through the usage of UAVs, realizes performances that are intermediate between the scarcer satellite segment and the denser stratospheric platform. While similar results are retrieved from different types of drones, the frequency of flights determines whether the data resolution can be estimated in seconds (with one hypothetical flight per day) or minutes (with one estimated flight per week).

It is easily visible how a synergetic approach would greatly increase the impact of the mission by combining more segments together.

4.4. Power and Energy Budgets and Collar Mass Estimation

By taking into account the retrieved data, the power budgets of the collars can be modified on the base on what was studied with WildTrackCube-SIMBA, by considering extended times of data acquisition and transmission. By considering the previously listed sensors and miniaturized systems, the most constraining feature is represented by the positioning sensor. Indeed, to achieve positioning, the GNSS sensors need an extended period of activation (generally around 30 to 60 s for a cold start fix). An alternative is represented by the INS sensors that need to be kept active to correctly propagate the position information through integration, by minimizing the measurements drift as much as possible.

A second major constraint is derived from the concept of operations. In the initial CubeSat demonstration operated with WildTrackCube-SIMBA, the collars have no methods to establish whether the satellite is in visibility or not; the collars execute their transmission commands regularly despite the actual presence of the satellite. This somehow limits the power and energy budgets, but still allows the collars to be operational for sufficient amounts of time. As will be seen, for other platforms (with particular regards to the atmospheric segment), the operability of a transmission command is paramount to reduce the power consumption of the SSM modules.

The analysis will be conducted by listing the following components and sub-units as responsible for the power consumption of the collar modules:

- The “idle mode” sub-units, i.e., all the units that are constantly active to operate the collar electronics. This subsystem groups the main controller and power distribution unit and the housekeeping sensors. Such units shall be kept active at all times. The unit is considered to be equipped with an internal memory capacity sufficient to acquire all the data from the collar, that will be later uplinked to the SSM modules on the vehicles. Through this unit, it will be possible to switch on and off all other components;
- The GNSS receiver, responsible for gathering the exemplar position. This will be operated at regular intervals, by taking into account that a single measurement can require a “cold fix time” of 30 to 60 s. The GNSS receiver will be operated by gathering fixes at regular intervals in order to reconstruct the exemplar’s motion once the data are received at the mission control station;
- The SSM LoRa transceiver, with the transmission active for regulated intervals each day. Due to the big impact on the energy budget, the transceiving module is supposed to operate in receive mode constantly, in order to receive commands from the other segments to uplink the data. This feature is not present on the WildTrackCube-SIMBA satellite mission, therefore the energy budgets will be reported with the current demonstration set-up (without a trigger) and with an extension with a trigger;
- The sensors, i.e., attitude sensors for position propagation and temperature, humidity and health sensors on the collar. The duty cycle on such modules will be regulated as needed. The inertial sensors are supposed, in some cases, to be coordinated to the GNSS chip operations.

Table 5 reports the energy budgets for the scenarios related to the UAV and atmospheric segment usage.

Table 5. Atmospheric segment energy budget.

Atmospheric Segment Energy Budget		**Fixed-Wing Drone (by Supposing 1 Flight per Day, Allowable Time Interval: 1 Packet per Collar Every 46 s)**		**Rotary-Wing Drone (Supposing 1 Flight per Day, Allowable Time Interval: 1 Packet per Collar Every 68 s)**		**Rotary-Wing Drone (by Supposing 1 Flight per Week, with 1 Packet per Collar Every 8 min)**	
Component	**Peak Power (mW)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**
GNSS receiver	127.5	5% (Active for 1 min every 20 min)	153	5% (Active for 1 min every 20 min)	153	1% (Active for cold fixes every 1.5 h)	31
SSM transmitter	415	5% (Active for 2 s every 40 s)	498	3.3% (Active once per minute)	1811	0.47% (Supposed for 80% of the flight time)	47
SSM receiver	25	100%	600	100%	600	100%	600
Sensors	75	100% (Constantly active for position propagation)	1800	100% (Constantly active for position propagation)	1800	0.4% (Active for 2 s every 8 min for data logging)	7.5
Idle mode components	15	100%	360	100%	360	100%	360
Total			3411		3245		1045

When computing the collar’s expected weight, the fixed- and rotary-wing segments with daily flights present minor differences, namely with 19 and 18 cells needed for one year of operations (with a total weight of 1.85 and 1.77 kg), or with 37 and 35 cells for a two-year duration of the energy system (with a total weight of 3.44 and 3.25 kg). When dealing with the final envelope considered, with weekly flights, the operations are compatible with the inclusion of 6-cell battery packs for one-year operations, totaling 0.65 kg of collar mass, or 12 cells for 1.12 kg for two-year operations.

A comparison of the obtainable data among all platforms is presented in Table 6.

Table 6. Daily energy budgets and collar weight estimation for all segments.

Flight Segment and Scenario	**Daily Energy Consumption (mWhr)**	**Number of Battery Cells Needed**		**Expected Collar Mass for 1- and 2-Year Operations**	
		1 Year	**2 Years**	**1 Year**	**2 Years**
Satellite, no trigger	1312	8	16	0.8 kg	1.45 kg
Satellite, with trigger	1076	6	12	0.7 kg	1.3 kg
Stratospheric, continuous positioning	6158	34	67	3.2 kg	6.3 kg
Stratospheric, sporadic positioning	3696	20	40	2 kg	3.9 kg
Fixed-wing drone, daily flight	3411	19	37	1.9 kg	3.6 kg
Rotary-wing drone, daily flight	3245	18	35	1.8 kg	3.4 kg
Rotary-wing drone, weekly flight	1045	6	12	0.7 kg	1.3 kg

As a general comment on the energy budget analysis and collar weight determination, the selected mission design never allows collars below 0.7 kg, which suggest a usage on animals with no lower mass than 70 kg, i.e., medium-size and large mammals or reptiles. The best performances in terms of mass reduction are given by the space segment, which is also constrained by a relative scarcity in data resolution, and by the rotary-wing drone's weekly flights, that combine a good data resolution (with packets every 8 min) to a significant mass reduction. The stratospheric segment, when considering a continuous acquisition of data from the positioning sensors, gives an estimated mass of more than 3 kg per year of operations. Such value can be mitigated by rarifying the number of positioning measurements to more acceptable intervals and by increasing the frequency of the other sensors measurements. In these regards, performances and mass determination are similar between the secondary mode of the stratospheric segment and both drone mission envelopes with daily flights and more dense data acquisition.

4.5. Cost Estimation

The deployment of the presented mission with the described variety of mission segments requires an estimation of the total costs. A rough order of magnitude cost estimation has been performed by taking into account different features:

- The platform costs, i.e., the costs needed to develop the in-flight platform for data relay. Satellite tracking has been delegated, in resemblance to the WildTrackCube-SIMBA mission, to a single 1U CubeSat development, while HAPS tracking has been delegated to a single experimental module to be fitted on a large stratospheric platform (otherwise, the costs can amount even to hundreds of thousands of Euros). An option of the implementation of weather balloons, with much lower development costs, will be presented within the stratospheric segment by taking into account that this will lead to reduced performance, but with good in-flight hardware demonstration capabilities. For the two typologies of UAVs, the total cost of the drone model will be taken into account. The option of weekly flights will explore the average rental costs for similar platforms to provide a term of comparison with the actual procurement of the UAVs;
- The in-flight unit costs, that may change by taking into account the technology readiness levels and robustness of the components ready to fly. While in the satellite case, the implementation of an in-orbit, spaceflight-ready SDR is taken into account, general purpose SDRs are supposed to be implemented in the stratospheric segment. The drone in-flight data relay units are supposed to be built in four specimens in order to provide replaceability of parts with more laboratory (low-TRL) electronics.
- The costs for mission support and ground support equipment. These will include the development of a ground control station for the satellite or stratospheric mission, possible qualification and support hardware to be used at ground for the components and collars handling. As will be seen, this finds the interest of, almost in an exclusive case, the space and stratospheric segments.

As will be presented, the costs will not include the personnel costs, which are difficult to quantify if not with a case-by-case approach. The collar costs, intended as the development costs for 100 wildlife collars, are not included in the analysis as this is made for comparing or combining the segments. An estimation of 100 collars deployment can be around EUR 30,000, which will be added to the segments' development costs.

The cost estimation table is presented in Table 7.

All the different segments explore the possible realization of the mission with different order of magnitude of costs. While the cumulative price while realizing more mission segments will be explored and presented in the discussion paragraphs, it is worth noting how this will be calculated for the drone segment, the platforms and in-flight unit. As for the comparison among the different segments, the most affordable and easy to realize are obviously the drone segments. The two cost options among the typologies are comparable to the cost of the ground segment with the collars' implementation, and the segment cost is comparable to the drone service rental by considering approximately 15 flights, making the two more conventional options (with the procurement of the drone platform) overall more affordable and convenient in the presented scenario.

Table 7. Cost budget.

Feature	Space Segment Costs (EUR)	Stratospheric Segment Costs (EUR)	Weather Balloon (as Complement or Alternative to Stratospheric Segment) Costs (EUR)	Fixed-Wing UAV Costs (EUR)	Rotary-Wing UAV Costs (EUR)	Rotary-Wing UAV with Weekly Flights and Rented Platform Costs (EUR)
Flight platform and launch	550,000	130,000	1000 to 3000 per flight	25,000	20,000	1500 per flight
In-flight Unit	50,000	25,000	500 per flight	2000	2000	2000
Support and Ground support equipment	25,000	5000	2500	0	0	0
Total estimated costs	625,000	160,000	2500 + 1500–3000 per flight	27,000	22,000	2000 + 1500 per week

The next paragraph will provide a comprehensive review and discussion of the considered performance analyses with some examples for future implementation of the mission.

5. Results Discussion and Possible Application Scenarios

In order to comprehensively discuss the obtained results, a summary table of all the performed analyses is reported in Table 8.

The review of the analysis shows how all the platform and mission segments insist on different levels of mission complexity and costs, overall collar performance and weight, data resolution and scanned areas. With respect to the implementation of UAVs in the SIMBA mission, the atmospheric segment with the deployment of drone flights provides a very good trade-off between ease and lower costs of implementation, in-flight hardware complexity reduction (which is reduced as it needs to assure few minutes per day of operations with the possibility of introducing maintenance activities at any time) and achievable data resolution and time intervals. While the fixed- and rotary-wing drone present significant differences only when computing the area coverage, the opportunity to perform less flights and to implement less frequent data acquisition relaxes the requirements and constraints on the collar batteries, arriving to a weight estimation very similar to the satellite segment.

It will be highlighted now how the best results are achievable with a synergetic approach, i.e., by combining the atmospheric segments together with the other analyzed segments. The chart presented in Table 9 will aim at identifying aims, scope and target species. This last task will be executed by adopting a conservative rule by considering the collar as approximately 1% of the adult exemplar’s total weight. Given the scenario and case study, species selection will be primarily directed towards terrestrial mammals in the census of the National Parks of Kenya. Three possible approaches will be analyzed, with the joint implementation of space, stratospheric and atmospheric segments, with the combination of space and stratospheric segments stand-alone with the atmospheric segment, and with a final comparison with the atmospheric segment stand-alone as a cost reduction possibility.

The approaches will be addressed by stating the services offered by the combination of mission segments. In this framework, the following will be analyzed:

- The possibility of HWC risk assessment and surveillance through continuous monitoring of the animals, while the platforms are operational;

- The possibility of tracking migratory species and the method preferentially used;
- The chance for high data density monitoring by realizing, potentially, more than one packet per minute;

The analysis is presented in Table 9.

Table 8. Summary of the computed budgets and analyses.

	Feature	**Satellite Segment**	**Stratospheric Segment**	**Fixed-Wing Drone**	**Rotary-Wing Drone**
Link budget	Slant distance [km]	1000	172.8	1.1–22.9	1.1–22.9
	Data rate [bps]	111.9	2278.65	9114.58	9114.58
	Link margin [dBi]	+5.88	+5.56	+15.0 (high altitude)–+41.1 (low-altitude)	+15.0 (high altitude)–+41.1 (low-altitude)
Area coverage	Vehicle-to-collar maximum ground distance [km]	1000	170	6–23	6–23
	Covered area [km^2]	Entire Earth surface (every 7–8 days)–3 × 10^6 (per pass)	90,000	120–600	12–1000
	Time over ROI	3 min passes 2 times a day	Continuous, 1–2 weeks	80–90 min per flight	30–60 min per flight
Data budget	Type of packets and bits per packet	Normal, 96	Extended, 208	Extended, 208	Extended, 208
	Packets per collar per day	3	7572	1893	1262 (with daily flights), 180 (with weekly flights)
	Time interval between packets per collar	7 h	11 s	46 s	68 s (with daily flights), 8 min (with weekly flights)
Energy budget and collar weight estimation	Daily energy needed per collar [mWhr]	1076 (with trigger command)–1312 (with no trigger command)	3696 (with seldom activation of positioning sensors)–6158 (with continuous GNSS receiver activation)	3411	1045 (with weekly flights and rarer activation)–3245 (with daily flights and more frequent activation)
	Needed battery cells for 1- and 2-year durations	6–12 (with trigger), 8–16 (no trigger)	20–40 (seldom GNSS activation), 34–67 (frequent activation)	19–37	6–12 (weekly flights), 18–35 (daily flights)
	Estimated collar weight for 1- and 2-year durations	0.7–1.3 kg (trigger), 0.8–1.45 kg (no trigger)	2–3.9 kg (seldom activation)–3.2–6.3 kg (frequent activation)	1.9–3.6 kg	0.7–1.3 kg (weekly flights)–1.8–3.4 kg (daily flights)
Cost estimation	Estimated platform deployment cost	EUR 625,000	EUR 160,000 (with weather balloon deployment at EUR 2500 + EUR 1500–3000 per flight)	EUR 27,000	EUR 22,000 or EUR 2000 + EUR 1500 per flight (weekly)

Table 9. Synergetic approaches to wildlife radio-tracking mission.

Feature	Option 1 (Satellite + Stratospheric Platform + Fixed-Wing Drone)	Option 2 (Satellite + Rotary-Wing Drone)	Option 3 (Stratospheric Platform + Fixed-Wing Drone)	Option 4 (Drone Stand-Alone)
Covered area	Entire Earth surface (with few packets a day), 90,000 km^2, continuously	Entire Earth surface (with few packets a day), up to 600 km^2 with daily drone flights	90,000 km^2	Up to 1000 km^2 per utilized base
Packet and data storage strategy	Normal (96 bit) 3 times a day, extended (208 bits) continuously saved	Normal (96 bits) 3 times a day, extended continuously saved	Extended (208 bits)	Extended (208 bits)
Collar weight (1 year of functionality assured)	2 to 3.2 kg (depending on data acquisition strategy and positioning data frequency)	0.7 (weekly drone flight) to 1.8 kg (daily flights)	2 to 3.2 kg (conditioned by stratospheric segment)	0.7 kg (weekly flights) to 1.9 kg (daily flights)
Time interval between packets for each collar	11 s	46 s (daily flights) to 8 min (weekly flights)	11 s	Between 46 s and 8 min
Overall cost (including collars implementation)	~EUR 850,000	~EUR 680,000	~EUR 220,000	~EUR 57,000 for single drone procured
HWC risk assessment and surveillance?	**Yes**, with continuous monitoring from stratospheric segment	**No**, continuous monitoring not available	**Yes**, with continuous monitoring from stratospheric segment	**No**
Dependability	**Major** on stratospheric segment	**Minor**, systems are independent	**Major**, stratospheric HAPS has great complexity	**Minor/None**, only drone flights are needed
Tracking of migratory species?	**Yes**, worldwide through satellite	**Yes**, worldwide through satellite	**Partially**, while inside stratospheric segment coverage or by moving the drone take-off point	**No**, possible only by moving take off point
High density data?	**Yes**, every 11 s	**Yes**, through drone segment (with daily flights)	**Yes**	**Yes**, with daily flights
Minimum exemplar weight	200 to 320 kg	70 to 180 kg	200 to 320 kg	70 to 190 kg
Target species	African elephant (*loxodonta africana*), African buffalo (*Syncerus caffer)*	Blue wildebeest (*Connochaetes taurinus*), topi (*Damaliscus lunatus jimela*)	Common lion (*Panthera leo*), white rhinoceros (*Ceratotherium simum*), giraffe (*giraffa camelopardalis*), hippopotamus (*hippopotamus amphibius*)	Mountain bongo (*Tragelaphus eurycerus isaaci*), sable antelope (*Hippotragus niger*)

While the target species specification already gives some hints on the possible applicability of this study, the performance table with synergetic approaches highlights the following:

- A comprehensive approach (Option 1) with the implementation of all segments requires a significant amount of funding (close to EUR 1 million) but restrains its field of applicability to large exemplars only. It is worth mentioning how this approach should consider the implementation of more typologies of collars, with reduced power consumption for migratory animals within several limits of mass (50–70 kg), or should consider a reconsideration of the weight limits;

- Option 2 realizes similar features to Option 1, with similar costs, by losing the HWC prevention capability due to the absence of a hovering platform. Such an approach can be adopted with significant funding implementation, but the reduction in performances is deemed excessive when compared to its relatively minor cost reduction (approximately 20%);
- Option 3 appears interesting because of its significant cost reduction (70% less than Option 1), while the performances are slightly reduced due to the absence of a highly migratory species tracking system through the satellite platform. The tracked species are superposable to Option 1, with the exception of largely migratory animals, which may not be tracked by the stratospheric platform;
- Option 4, with drone only, is reported to highlight how the synergetic approach can realize multiple objectives. With an extremely reduced cost (of less than 10% of the first approach), such a typology of mission can target lower weight species but without many of the identified services.

The whole analysis demonstrates how a synergetic approach involving stratospheric and aerial platforms could easily overcome the performance of a satellite platform, with more than 70% of the cost reduction, while targeting tracking and HWC prevention of large mammals in the Kenya National Parks. Satellite monitoring can still be implemented, with a particular focus on future constellation implementation, given the aspects of low dependability (which are very pressing on the stratospheric platform implementation). A performance graph was evaluated on the base of the costs, collar weight and time resolution, and it is presented in Figure 5.

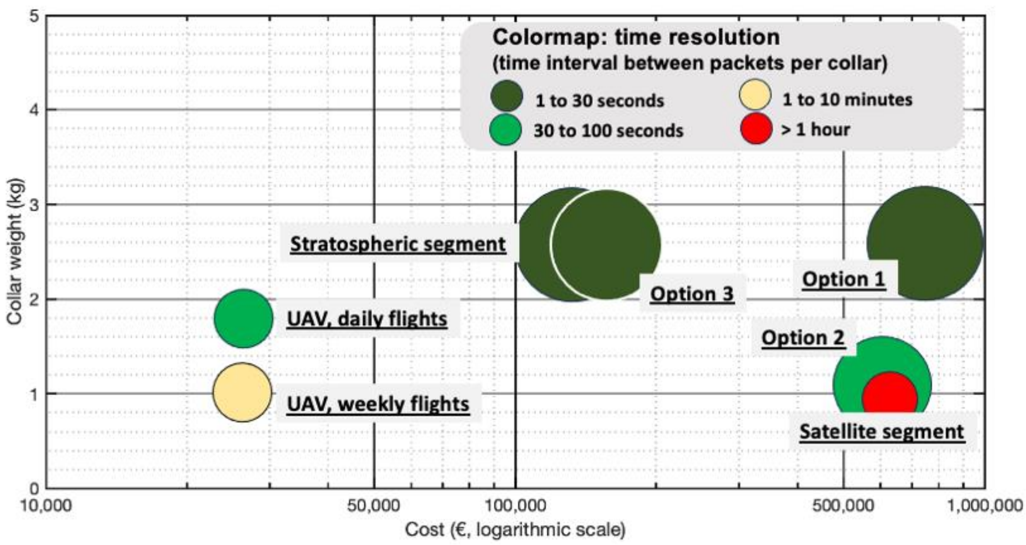

Figure 5. Performance map related to costs, collar weight and time resolution.

The performance map provides a further overview of the design and analyses results and can serve as a quick look-up table for similar missions' evaluation. While the satellite segment and Options 2 (satellite + drone) and 1 (satellite + stratospheric platform + drone) present similar costs (or are at least in the same rough order of magnitude estimation of costs), Option 1 presents a way higher time resolution while requiring more weight on the collars. Vice versa, the satellite segment stand-alone and its integration with a UAV in Option 2 presents a lower resolution and therefore a lower collar weight.

In the middle of the graph, Option 3 (stratospheric + drone) presents an almost equal cost to the stratospheric platform experiment implementation, while disposing of one more segment. The UAV segment stand-alone, with the two options of weekly or daily flights, ensures minimum costs and a good time resolution.

From all the performed considerations, it is possible to map the design steps and the expected final results, and to re-phrase them as design drivers. This is presented through the graph in Figure 6.

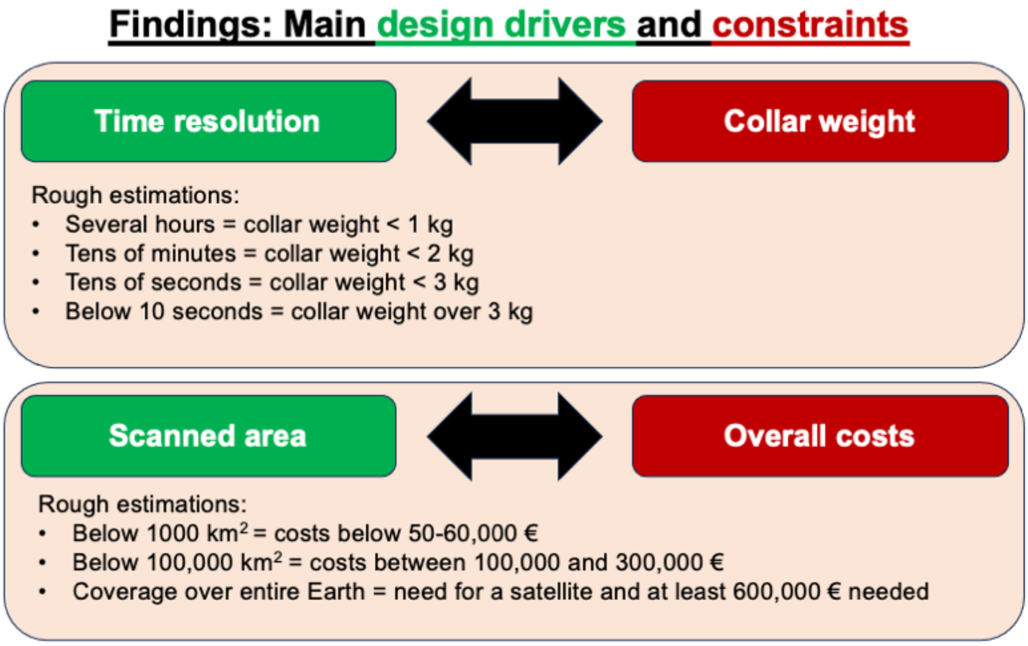

Figure 6. Visualization of main design drivers and constraints.

The graph can be read by improving the main design drivers (left-hand side) or by minimizing the constraints (right-hand side) on the mission. The evaluated levels of performance have been included to give a preliminary overview of the achievable performances. This result is also important for future mission design, as it allows the immediate correlation of performance variables and the immediate including of dependencies in the design loops.

6. Conducted and Planned Tests on in-Flight Platforms

This paragraph reports the conducted (preliminary or operational) tests conducted on satellite, stratospheric and drone platforms in the future perspective of an implementation of the monitoring mission for the evaluation of the performances of the different segments.

6.1. Satellite Operations and Technology Demonstrations with WildTrackCube-SIMBA

Several experiments have been conducted by the WildTrackCube-SIMBA satellite for collar data reception and re-transmission towards ground stations. A dedicated testing campaign on the collar-to-satellite transmission was carried out in Kenya in November 2023. Such a campaign demonstrated the performances of the established SSM link between the prototype collars and WildTrackCube-SIMBA. The most important test with satellite reception took place on 11 November 2023, with the collar transmitting from the Italian Space Agency Broglio Space Center in Malindi, Kenya, with a high-elevation pass of the satellite. During the test, the prototype collar was constantly transmitting data packets to the satellite. The collar emissions were monitored by a SDR in proximity to the collar, whose spectrogram is presented in Figure 7.

(a) (b)

Figure 7. The collar prototype transmission box (**a**) and the spectrogram from the collar unit transmission at a close proximity during the uplink tests (**b**).

The satellite pass had a maximum elevation of around 83 degrees above the horizon, and a duration of 11 min (from 07:56 UTC to 08:07 UTC). The test successfully demonstrated the functionalities and performances of WildTrackCube-SIMBA in data transmission. A table with the achieved results in terms of minimum and maximum elevation successful uplink of packets is reported in Table 10.

Table 10. Results from the communication test performed in Malindi, Kenya, in November 2023.

	Time	Elevation
Lowest elevation	08:00:07 UTC	43.16 degrees
Highest elevation	08:01:17 UTC	83.60 degrees

The conducted tests proved the well functioning of the transmission link between the prototype collars and the WildTrackCube-SIMBA CubeSat.

6.2. Rotary-Wing Drone Operations Preliminary Test

The same SSM transceiver implemented in the satellite tests was used for a preliminary link verification on-board a rotary-wing UAV in-flight. The test was conducted by using a transmitter on-board the drone and receivers at ground, drafting spectrograms and recording the signal strength upon reception. A side experiment was conducted for verifying the capabilities on narrow-field multi-lateration with multiple receivers, which is an extension of the conducted verification. The link was then verified with down link features, as per simulation of trigger command transmissions. The airborne hardware was identical in set-up and functionalities to the collar, proving the modularity and flexibility of operations of the investigated technical solutions. The airborne test hardware is presented, together with the rotary-wing drone, in Figure 8.

The test was successful in providing a functional verification of the airborne data relay hardware and in testing the transmission link with ground-based units, by confirming the actual data rates foreseen by the prepared link and communication system to verify. A spectrogram of the received samples during the test is reported in Figure 9.

Figure 8. UAV test for the SSM communication link: drone and collar configuration.

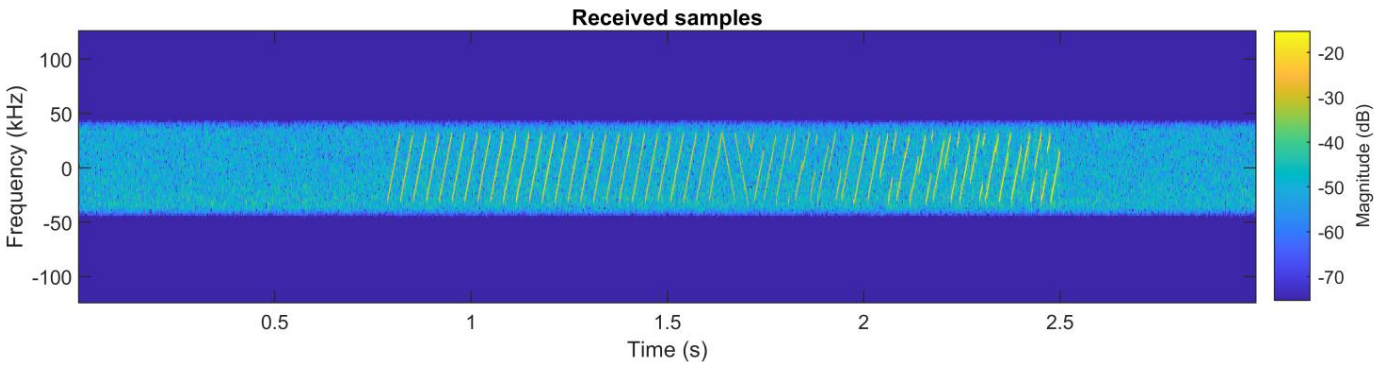

Figure 9. Spectrogram of the received samples from the UAV unit during the test.

The performed tests allowed for the confirmation of the performances of the collar-satellite link and for the preliminarily verification of the capabilities of the UAV radio-tracking system from the perspective of future operational implementation.

7. Conclusions

This study demonstrates the performances of CubeSats, stratospheric airships and UAV applications for wildlife radio-tracking through Spread Spectrum Modulation chips (using LoRa transmissions). The case study of the work is WildTrackCube-SIMBA, a 1U CubeSat mission launched in 2021 for the demonstration of Spread Spectrum wildlife tracking in the National Parks of Kenya. This study was addressed to the design of wildlife radio-collars for in-flight data relay from the listed platforms.

The main features of the segments differ in terms of covered area, time on target, implementation costs and technology readiness levels required. The ground segment is specified as the collar features that are primarily aimed at locating the animal and at preventing, when applicable, Human–Wildlife Conflicts, while inertial, heartrate and health sensors can be implemented. The space segment design is based on the WildTrackCube-SIMBA features, with Software Defined Radios composing most of the data relay in-orbit payload and with a generic sun-synchronous orbit at 550 km of altitude. The stratospheric airship implements the design of a generic electronics payload to be equipped on a station-keeping high altitude platform station. The mix of a relative proximity to the ground, low altitude, high range of visibility and overall lower costs makes it interesting for the feasibility study. The UAV segment is detailed with EUR 15–20,000 drones with bolth fixed and rotary wings.

The performances have been analyzed in terms of the link budget and quality, area coverage, data budget, energy consumption, collar weight and costs. The link budgets present extremely low margins for the space segment, while all the other segments allow the steady and high-quality transmission of Spread Spectrum data. The allowable data rate increases when decreasing the altitude and slant range to the collars, spanning between approximately 110 bps and 9100 bps. Significant margins should be taken into account to allow the implementation of SDR data relay systems on future mission segments. The area coverage has been analyzed by taking into account the main features of the vehicles, dividing them between hovering and scanning vehicles. The total area coverage has been calculated as a function of the vehicle range and operational time and its altitude. The data budget has been addressed by estimating the total time interval among packets saved by the same collar, by taking into account a preliminary deployment of 100 collars. While the satellite shows the worst performances, with 1 packet every 7 h, the stratospheric platform shows the capability for a packet for each collar every 11 s. Intermediate capabilities, which are much closer to the stratospheric segment, are shown by the atmospheric segment. The energy budget calculations show the applicability of the study (when considering 1 year of operability of each collar) for medium–large weight mammals, by considering a minimum weight of 0.7 kg, spanning up to 2–4 kg per collar when considering higher consumption per day or a longer autonomy (up to 2 years). The drone segment appears to show the most conservative estimations of collar weight when reducing the data transmissions down to one per week and the acquisition time to once every 8 min. The cost estimation shows how the atmospheric segment can be realized with approximately EUR 30,000, while the stratospheric and space segment need hundreds of thousands of Euros to be properly implemented.

The data have then been combined to show the benefits of a synergetic approach to the problem. Particularly interesting data were derived by the inter-operations of satellites and drones, which show a lower dependability at a higher cost with high performances and global coverage, and by a mixed stratospheric–atmospheric mission, which reduces the maximum (with all segments deployed) cost by 70% while keeping most of the features active, yet with a high dependability on the availability of a HAPS. The drone segment stand-alone shows good features while not allowing for most of the identified critical features and services. Finally, the performance map and design and constraints dependencies have been evaluated in order to correlate the design degrees-of-freedom and to provide immediate dependencies to the design loops of similar missions. A preliminary verification of the conducted research has been conducted in Kenya and Italy through performance assessment of the satellite–collar link and through preliminary verification of the UAV data relay system.

Author Contributions: Conceptualization, P.M.; methodology, P.M. and R.G.; software, P.M., R.G. and L.F., validation, L.F., P.M. and R.G.; formal analysis, P.M. and R.G.; investigation, R.G. and P.M.; data curation, P.M. and R.G.; writing—original draft preparation, P.M. and R.G.; writing—review and editing, P.M., R.G. and L.F.; visualization, P.M.; supervision, A.N., G.S., M.J., F.P. and F.S.; project administration, A.N., G.S., M.J., F.P., F.S. and P.M.; funding acquisition, F.P. and F.S. All authors have read and agreed to the published version of the manuscript.

Funding: The WildTrackCube-SIMBA project is supported by the Italian Space Agency under the agreement "Accordo Quadro n.2020-30-HH.0".

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The launch of the spacecraft has been offered by the International Astronautical Federation (IAF) and GK Launch Services in the framework of the free launch competition organized for the 70th International Astronautical Congress (IAC) in Washington DC (2019).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Supplemental Data on System Budgets

Appendix A.1. Link Budgets

By starting from the satellite link budget, it is possible to compute a minimum satellite link budget (by considering a minimal positive margin over the link, in order to establish the maximum slant range ensuring a positive SNR), and an optimal satellite link budget (by considering a sufficient margin threshold while maximizing the data rate possible for large slant range communication). The link budgets are reported in Table A1.

Table A1. Space segment link budget with minimum and optimal elevations.

Feature	Minimum Satellite Link Budget (Minimum SNR)	Optimal Satellite Link Budget
Distance [km] and elevation [degrees]	1420/17 degrees	1000 (approx.)/30 degrees
Spreading Factor	11	11
Bandwidth [KHz]	62.5	62.5
Frequency [MHz]	868	868
TX Power [dBm]	17	17
Cable Loss [dBm]	2	2
Antenna Gain [dBi]	1	1
Outputs		
EIRP [dBm]	17.5	17.5
G/T [dB/K]	−25.64	−24.64
Free Space Path Loss [dB]	154.27	151.16
Nominal Bit Rate	111.9	111.9
Link Margin [dB]	+0.27	+5.883

The calculations over the space segment reveal how a positive SNR can be realized when the satellite is above 17 degrees of elevation, while an optimal link margin (>5 dBi) is encountered when operating above 30 degrees of elevation. Such a link can be realized with a Spreading Factor of 11, which is relatively high, and can ensure a nominal bit rate of only 111.9 bps for achieving a certain margin in in-orbit conditions. The link budget can suggest how platforms at a closer distance can realize better links with higher data rates.

The stratospheric segment link budget is presented in Table A2. An altitude of 30 km is taken as the reference value and a sufficient elevation (10 degrees) is considered.

Table A2. The LoRa link budget for the stratospheric mission segment.

Cases	Stratospheric Airship
Distance [km] and elevation [degrees]	172.8 (10°)
Spreading Factor	7
Bandwidth [KHz]	125
Frequency [MHz]	868
TX Power [dBm]	17

Table A2. *Cont.*

Cases	Stratospheric Airship
Cable Loss [dBm]	2
Antenna Gain [dBi]	1
Outputs	
EIRP [dBm]	17.5
G/T [dB/K]	−25.64
Free Space Path Loss [dB]	135.97
Nominal Bit Rate	2278.65
Link Margin [dB]	**+5.56**

A 5 dBi margin is realizable by keeping the SF at a lower value (7), with an improved bit rate of approximately 2300 bps, therefore realizing a higher performing link than in the satellite case.

Appendix A.2. Data Budgets

The detailed structures of the "Normal" and "Extended" packets are presented in Table A3.

Table A3. Considered packet structure.

	Type of Data	Normal Packet	Extended Packet
Overhead	ID and overhead	24 bit	24 bit
GNSS data	Number of GNSS satellites in visibility	8 bit	8 bit
	Latitude	24 bit	24 bit
	Longitude	24 bit	24 bit
Additional environmental and health data	Temperature and humidity	16 bit	16 bit
	Heartrate and attitude (INS) data	Not present	96 bit
	Total	96 bit	208 bit

Appendix A.3. Power and Energy Budgets and Collar Weight Estimation

The total daily energy budget will be calculated by considering the measured power consumption through the testing completed on the WildTrackCube-SIMBA collars, while viable solutions for the energy systems will be discussed. The energy budget for the satellite operations is reported in Table A4.

The WildTrackCube-SIMBA collars currently under testing are characterized by a consumption of approximately 1.3 Whr per day, while a 20% improvement can be expected in the energy consumption of a next version of the collar, that will equip the trigger functionality and the possibility to leave the chips in receive mode.

The next step is to evaluate the needed amount of batteries to secure, respectively, 1 and 2 years of operations for each collar. By taking into account the implementation of Li-SOCl2 primary battery cells, a 68 Whr cell has a weight of 93 g. In order to support 1 year of operations, 8 cells are necessary, with a total collar mass of 0.8 kg, while for 2 years of timespan, a collar of 1.45 kg is needed. The second case reduces the number of needed cells to 6 (1 year) and 12 (2 years), with collars of 0.76 kg and 1.32 kg, namely. The analysis is repeated for the stratospheric segment and reported in Table A5. Two cases are analyzed, with the collars constantly logging the animal position, and with a secondary case with a higher data rate dedicated to the sensors (which might be characterized by a higher resolution within the data packets of 208 bits), with a lower usage of GNSS sensors.

Table A4. Energy budget for the space segment.

Satellite Energy Budget (Allowable Time Interval: 1 Packet per Collar every 7 h)		**Without Satellite Transmission Trigger**		**With Satellite Transmission Trigger**	
Component	**Peak Power (mW)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**
GNSS receiver	127.5	5.55% (80 min per day)	170	1% (15 min per day)	25.5
SSM transmitter	415	6.94% (100 min per day)	692	0.007% (2 min per day)	0.79
SSM receiver	25	0%	0	100%	600
Sensors	75	100%	90	5%	90
Idle mode components	15	100%	360	100%	360
Total			1311.67		1076.29

Table A5. Energy budget for the stratospheric segment.

Stratospheric Segment Energy Budget (Allowable Time Interval: 1 Packet per Collar Every 11 s)		**Nominal Case: GNSS Sensors Constantly Logging Positioning Data**		**Secondary Case: GNSS Sensors Active Every 2 h, with Extended Usage of Sensors)**	
Component	**Peak Power (mW)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**	**Duty Cycle**	**Daily Energy Consumption (mWhr)**
GNSS receiver	127.5	100%	3060	0.8% (12 min per day)	25.5
SSM transmitter	415	18% (2 s per packet)	1811	18% (2 s per packet)	1811
SSM receiver	25	100%	600	100%	600
Sensors	75	18% (2 s per packet)	327	50%	900
Idle mode components	15	100%	360	100%	360
Total			6158		3696

In this case, the nominal case would present a collar design of 34 cells for a single year of operations, with a mass of 3.2 kg, and with 67 cells and 6.3 kg for 2 years of operations. The secondary mode case would then lead to 20 cells needed for 1 year, with 2 kg of collar mass, and 40 cells needed for two years, with approximately 3.9 kg of mass for each collar. It is evident how such collars might lead to a strong reduction in transmission and data acquisition intervals in order to allow smaller species to be supported, or they could fit only the biggest mammal species with the 1% total weight limit.

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