Title: A nano-satellite constellation for tracking and monitoring endangered wildlife in developing countries.

Primary Point of Contact (POC) & email: Jan-Hielke le Roux (15661563@sun.ac.za)
Co-authors: André Heunis, Gerhard Janse van Vuuren, Nico Rossouw, Nico Calitz, Douw Steyn, Muhammad Junaid, Mohammed Bin Othman, Willem Jordaan, Christo Groenewald, Arno Barnard
Organization: Stellenbosch University

(X) We apply for Student Prize.

(X) Please keep our idea confidential if we are not selected as finalist/semi-finalist.

Need

The tracking and monitoring of wildlife is required by numerous nature conservation organisations around the world to study and preserve endangered animals, especially in developing countries across Africa and South America [1]. Available solutions are either very expensive or rely on intensive fieldwork using volunteers [2]. There is a need for an affordable, preferably free, tracking and monitoring solution specifically aimed at developing countries that can be deployed in any location. It should be innovative enough to replace the use of conventional tracking and monitoring methods by reducing system cost and required manpower.

Mission Objectives

The following objectives have been set for the mission:

1. Create an affordable solution to current animal tracking and monitoring problems for conservation organizations in developing countries across Africa and South America.
2. Develop a constellation of small satellites, using mostly current commercial electronics to reduce development costs, while maintaining high performance in small form factors.
3. Develop an Amateur band communication payload, simplifying the licensing requirements and costs required by ground devices to transmit at the required power levels.
4. Deploy the constellation in a pearl-string configuration, in a polar sun-synchronous orbit, to provide extensive communication coverage over Africa and South America.
5. Automating existing ground station(s), to reduce operational manpower requirements and develop low cost modular ground stations for areas with little or no infrastructure.

Concept of Operations

This mission consists of three key elements: the space segment, ground segment, and user segment. The space segment will consist of a constellation of 12 satellites, evenly spaced in a 900 km sun-synchronous orbit. Given the chosen orbit and coverage pattern every point on earth within the focus areas of Africa and South America will receive an access time of 105 minutes to the constellation every 10.25 hours. The constellation will also act as a communications relay utilizing Inter Satellite Links (ISL) to transfer data between constellation satellites. Data will be buffered within the satellites if no ground stations are available and any constellation satellite can download gathered tracking and monitoring data to compatible ground stations. For the ground segment, potential ground stations will be spaced along various longitudes surrounding Africa and South America to provide active ground station connections for these continents. The ground stations will also transmit data to a cloud based server, after which users can access the information through an online web portal.

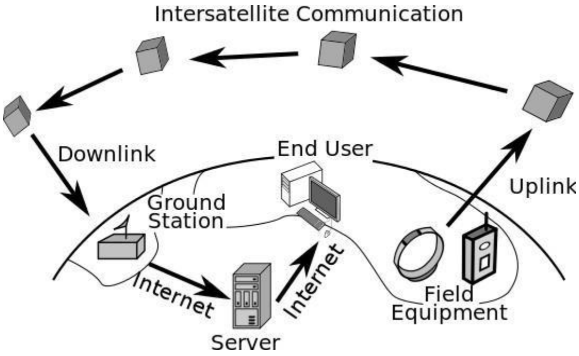

Figure 1: System Communication Path

The user segment encompasses all devices generating data for use by nature conservation organisations. Use cases for the system were compiled after discussions with members of the Cape Leopard Trust [3] and the Department of Conservation Ecology and Entomology of Stellenbosch University. Applications include satellite tracking combined with active tracking collars and camera trap status monitoring. Camera traps are placed in remote locations which are difficult to access. There currently exists no system providing near-continuous monitoring of camera

traps. Organisations will benefit by using this constellation since it will allow them to access devices multiple times per day and only enter the field for device maintenance.
The project will be managed as a non-profit endeavour to assist in providing an affordable solution to users. The ultimate goal is to provide the service for free, depending on the success of alternative funding options, like crowd funding. Users should only be required to cover the costs of their ground equipment.

Key Performance Parameters

The key performance parameters for this project include:

- **Affordability** - The affordability of the equipment is a key aspect as conservation organisations often operate on tight budgets. Development goals are aimed at keeping the development and maintenance costs of the system as low as possible.
- **Communication Reliability** - Reliable communication for the user segment is essential as some applications will require that the device communicate to the system twice a day. Reliability is not only linked with the equipment in the field but the satellite constellation and the continuous operation thereof.
- **Satellite Coverage** - Full and near-continuous communication coverage of developing countries in Africa and South America. These continents are covered due to the abundance of wildlife, large area of required coverage and the lack of infrastructure for alternative solutions.
- **Communication Bandwidth** - There is a reasonable probability of having many tracking collars and other monitoring devices situated in a small area. This leads to many devices requiring an equal opportunity to upload information during a constellation pass. Each device must be guaranteed an upload opportunity every constellation pass.

Space Segment Description

The space segment consists of 12 satellites equally spaced (30° separation) in a 12am/12pm sun-synchronous orbit. This segment consists of the designs for the communications, the attitude determination and control system (ADCS), as well as the power budget and estimated weight.

Link Budget

Each up/downlink pair will operate on the same frequency in half-duplex mode. A half-duplex link is acceptable in this case as continuous data streaming from a single node is not required. This also reduces antenna requirements on the satellite and field equipment. A single node will only require a short connection to upload data. The communication will make use of connectionless AX.25 framing with custom high level protocols controlling further functionality.

Item	Symbol	Units	Field Uplink	Field Downlink	ISL	Sat Uplink	Sat Downlink
Frequency	f	GHz	0.436	0.436	2.4	1.26	1.26
Transmit Power	P	W	1.00	1.00	2.00	2.00	1.00
Transmit Line Loss	L_l	dB	1.00	1.00	1.00	1.00	1.00
Transmit Antenna Gain	G_t	dBi	-4.00	4.00	11.00	10.00	7.00
Equivalent Isotropic Radiated Power	EIRP	dBW	-5.00	3.00	13.01	12.01	6.00
Propagation and Polarization Loss	L_a	dB	0.30	0.30	0.30	0.30	0.30
Propagation Path Length	S	Km	2069.49	2069.49	3767.44	2069.49	2069.49
Space Loss	L_s	dB	151.56	151.56	171.58	160.77	160.77
Receive Antenna Gain	G_r	dBi	4.00	-4.00	11.00	7.00	10.00
Noise Figure	F	dB	3.00	3.00	2.00	2.0	2.00
Data Rate	R	bps	1200	1200	9600	9600	9600
Implementation Loss	L_l	dB	2.00	2.00	2.00	2.00	2.00
E_b/N_0	E_b/N_0	dB	13.96	14.02	12.28	18.92	14.15
Bit Error Rate	BER	-	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
Required E_b/N_0	REQ E_b/N_0	dB	10.50	10.50	10.50	10.50	10.50
Margin		dB	3.46	3.52	1.78	8.42	3.65

Table 1: Link Budget for communication between ground-based devices and constellation

A full constellation pass lasts for 92 minutes which gives a throughput of 828 kB per constellation pass for a single area. A connectionless AX.25 frame with 32 bytes of information payload consists of 51 bytes per frame. Generally devices will only transfer small amounts of data, for example tracking collars will transmit GPS logs while other devices will only deliver status messages. Given that a single pass can deliver 16 235 frames and each device delivering 1kB of data, the bandwidth will be enough to service up to 519 devices in the same area.

Antenna Coverage

A swath width of 3 500 km was chosen as it covers the width of Africa south of the equator. This allows the constellation to service the full African and South American continents within only two passes as shown in Figure 2 (simulated in SaVi [4]). With this swath an antenna on the satellite requires a view angle of 113° and the elevation angle at the edge of the coverage pattern is 17.66°. This elevation angle combined with the drifting motion of the constellation ground track should provide line-of-sight over tree lines and hills and minimise the chance that a field station cannot communicate due to its surrounding terrain. This coverage, with the gains specified is achievable with a dipole antenna on both the satellite and ground equipment. An antenna length of roughly 33cm (half wave length) is required and it can easily be implemented as a deployable structure on a nano-satellite. This size antenna can fit in the strap of a tracking collar, on an animal, and easily be added to a camera trap. The ISL will make use of patch antennas on opposite facing sides of the satellite to communicate with the neighbouring constellation satellites. A beam width of roughly 10° is required to limit interference with the other ISLs in the constellation.

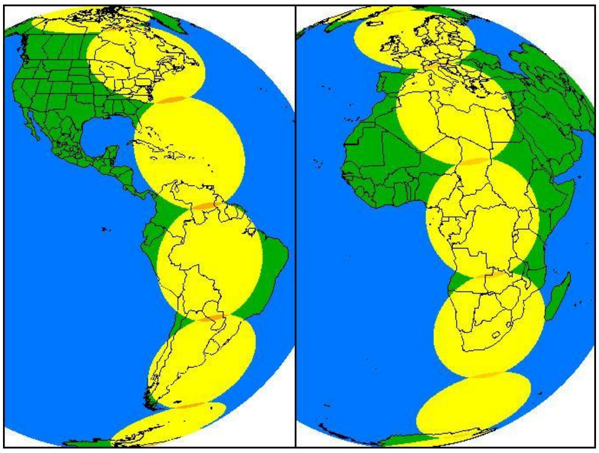

Figure 2: Constellation Ground Coverage

ADCS

The main goal of the ADCS of each satellite is to maintain a nadir-pointing attitude and to point the ISL antennas. Other functions of the ADCS are to:

- de-tumble the satellite after launch;
- phase and maintain the satellite in the desired orbit;
- de-orbit the satellite at the end of its lifetime.

To achieve these goals, a set of ADCS control modes is defined and the hardware used for each is shown in Table 2 below. Each satellite will be in an uncontrolled tumble directly after launch. Firstly, the ADCS will have to de-tumble the satellite. Thereafter the satellite will perform an orbit phasing manoeuvre in order to achieve a 30° angle between each satellite. During normal operation, the satellite will be in nadir pointing mode. And, finally, the satellite will be in de-orbit mode at the end of its lifetime. A sun tracking mode will be included as a safe-mode during de-tumbling and normal operation. The ADCS hardware will be chosen to satisfy a control accuracy of less than 3° (3-sigma).

Component	ADCS mode(s)
Earth horizon sensor	Nadir pointing
Sun sensor	Nadir pointing, sun tracking
Magnetometer	Detumbling, nadir pointing, sun tracking
Magnetic Torquer (x3)	Detumbling, nadir pointing, sun tracking, angular momentum management
Y-axis momentum wheel	Detumbling, nadir pointing
Propulsion system	Orbit phasing, deorbiting

Table 2: ADCS Components and Control Modes

The worst case orbit phase manoeuvre that any satellite in this constellation will need to perform is chosen as 180° phase shift over a maximum period of 30 days. The propellant mass required to perform this worst case manoeuvre is calculated as approximately 8 g per kg of satellite mass. Satellite masses of past missions with similar phasing requirements, varied around 10 kg. With an estimated mass of roughly 12 kg, each satellite in this mission will require about 96 g of propellant. A Y-axis momentum wheel will be included to ensure gyroscopic stiffness when using the propulsion system, which will also be in the Y-axis.

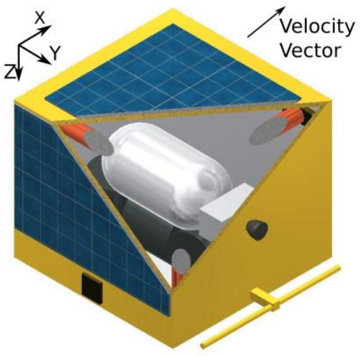

Figure 3: CAD Concept

Power Budget

The 12am/12pm nature of the sun-synchronous orbit ensures that the sun-angle of the XY plane will be perpendicular to the sun while the Z angle changes. A preliminary analysis of the satellite's power requirements yielded an orbit average 5.51W. As each satellite is in sunlight 66% of its orbit, solar panels fixed to the body of the satellite will be used to generate power and recharge the batteries. To maintain the inter-satellite link, solar pointing of the satellite is not an option. Therefore, the -X, +X, and -Z faces of the satellite will hold solar panels. Satellite power requirements can be met by sizing each body-mounted solar panel to 0.3m x 0.21m.

Orbit/Constellation Description

The constellation design for the mission is based on the access times required by organisations as well as the frequency of overpasses. An orbital inclination of 99.033° was chosen to ensure that the polar orbit would remain sun-synchronous, resulting in access to the constellation at least twice a day from anywhere in the target continents. The 12am/pm orbit simplifies the power system design by removing the requirement to implement solar panel sun tracking.
Given the designed antenna beam width, at least 12 satellites are required to provide continuous access during a constellation overpass. This gives an access time of 92 minutes per constellation overpass. Depending on funding, as an extension to the first 12 satellite constellation, a second set of almost identical satellites can be placed in a similar orbit at a 90° offset in RAAN (6am/pm). For clients this would reduce the constellation revisit time to just over 5 hours and increase the total access time to 368 minutes per day.

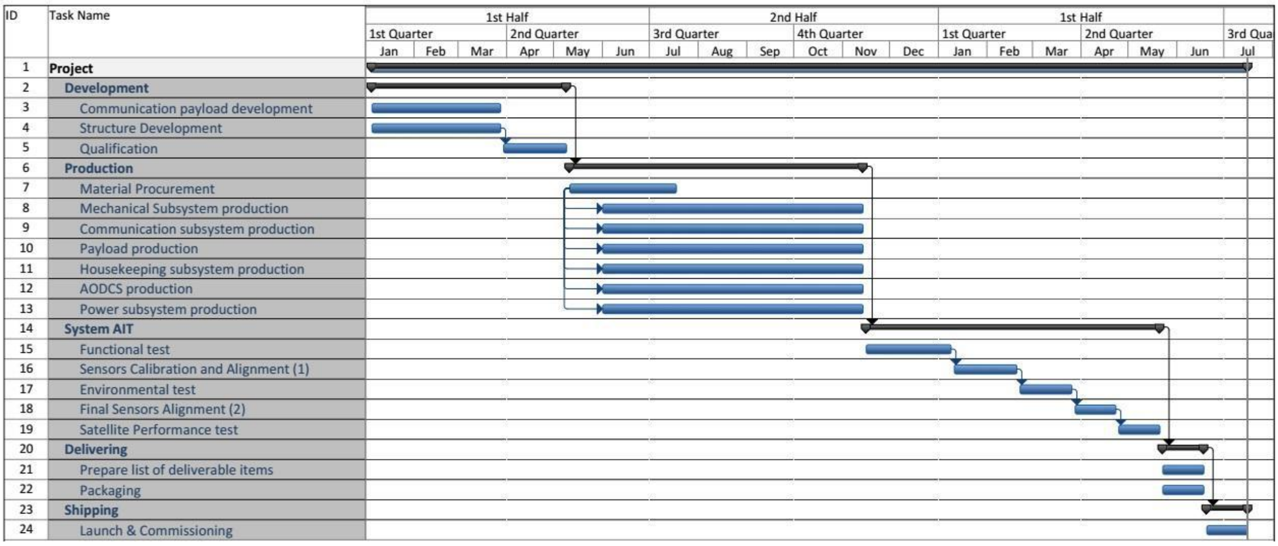

Figure 4: Planned Mission Schedule

At the constellation altitude of 900 km, a balance is struck between maximising the beam coverage area on the earth and keeping the communication path length low. This altitude also keeps the constellation from travelling through the Van Allen belts (except for the South Atlantic Anomaly region and the poles) while minimising the aerodynamic drag on the satellites. The constellation's form (and therefore, the ISL quality) is easier to maintain and reduces the requirement of fuel used for phasing and orbit maintenance.

Implementation Plan

The implementation will consist of three phases. The first phase of the mission involves the development and testing of field devices. Proprietary low cost devices will be constructed which will be based on previous work conducted at Stellenbosch University regarding satellite tracking collars [5]. Satellites already in orbit will be used to test the communication capability of the field devices. The second phase involves launching three to four satellites separated by 30° (similar to the final constellation). In this configuration, the constellation will provide access of between 1 and 25 minutes from any point on earth, every 12 hours. This phase will be used as a proof of concept and operation and reduces the risks involved when launching the 12-satellite constellation at once. The system design can be altered if required during the final stage. To save on launch expenses, a single launch can be used to deploy the remaining satellites. If the project proves successful and the demand is beyond the capabilities of the single constellation it can be expanded by adding a second constellation as described in the previous section. In this case alterations to the satellite's thermal design will be required given that the 6am/6pm orbit is a full sun orbit.
By using a multi satellite constellation, failure of an individual satellite will not result in total system failure. The only effect will be reduced performance of the service in terms of data throughput and access time. The mission implementation schedule for the initial constellation can be viewed in Figure 4.

Life cycle cost estimate

A preliminary cost analysis based on similar projects resulted in the following cost estimates:

- € 102,887 for the component costs involved in satellite design and development;
- € 1,234,664 for the component cost of 12 satellites;
- € 1,000,562.88 for the labour costs of 25 engineers over 18 months;
- € 1,098,520 for launch and operations, included in this amount is: € 154,392 for three launches, € 22,073 for launch logistics, € 22,055 for commissioning, € 900,000 is included as ongoing operational costs over for the planned 10 year lifetime of the constellation.

By using professional labour and taking conservative estimates, the total cost of the mission will be roughly € 3.43M over the specified 10 year lifetime. To assist in developing an affordable solution, the mission will be developed, deployed and maintained by a non-profit organisation. This opens alternative funding opportunities through donations, research funds as well as crowd funding (which can amount to over € 1M). Without any alternative funding an average income of € 28,580 per month is required to cover the mission costs, which can be generated by operating on cost-per-data-volume price for organisations and a monthly access fee.

Risk identification

The availability of reliable and affordable components for the satellites as well as ground devices can delay development and increase manufacturing costs. To reduce the impact of non-dedicated ground station access, participating ground stations will be sought on as many separate lines of longitude as possible to ensure the constellation always has at least one ground station connection. The impact of launch failure and loss of individual satellites during operation are mitigated by the procedures discussed in the implementation plan. Lack of alternative funding could make the project infeasible. However, the number of organisations and researchers utilising the devices being targeted by the proposed service is growing. This, along with global environmental awareness, should motivate potential donors and financial support.

Summary

By combining existing technologies in a novel way this mission will achieve the objectives above.

References

[1] WWF Priority Places, [Online], https://www.worldwildlife.org/places
[2] Wildlife Africa Conservation Team (ACT), [Online], http://wildlifeact.com/
[3] Cape Leopard Trust, [Online], www.capeleopard.org.za
[4] SaVi - satellite constellation visualization, [Online], http://sourceforge.net/projects/savi
[5] D.J. Warnich, "Tracking collar and infrastructure for leopard research", University of Stellenbosch, December 2012
[6] ARKYD Kickstarter project, [Online], https://www.kickstarter.com/projects/arkydforeveryone/arkyd-a-space-telescope-for-everyone-0