<Constellation Mission>

**Title:** Satellite constellation to relay GPS signals to Earth with the goal of increasing location accuracy and promote the development of autonomous vehicles

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## Need

Advancements in autonomous vehicle technology offer many future solutions, from agricultural harvesters following orchard lines to humanitarian robots able to perform dangerous tasks to save human lives. These solutions are especially valuable in developing countries where ecological disasters are prevalent and autonomous machinery is limited by the lack of complex industry. Currently, the Global Positioning System (GPS) does not allow the accuracy needed to reduce the complexity of autonomous machines. [1]

However, to increase the operational efficiency of autonomous machines, this mission aims to increase GPS accuracy by launching a constellation of small satellites in low earth orbit to augment the existing GPS network, without the need for new ground infrastructure. While a similar system, the Wide Area Augmentation System (WAAS), currently exists, it requires extensive ground infrastructure and geostationary satellites to function. [2] Furthermore, environmental factors such as buildings, tree-cover and GPS satellite positioning can drastically degrade the accuracy. [3]

## Mission Objectives

The mission objectives are listed below in descending priority:

1. Receive, augment and relay GPS timestamp.
2. Increase GPS accuracy of machines operating in non-open-sky conditions.
3. Maintain a consistent increase in satellites in sky of developing areas.

## Concept of Operations

The various operational groups of the mission are described in this section.

- Ground Segment role:
    - Ground Station
        - Receive operational data from satellites.
        - Transmit commands to satellites.
    - Autonomous machine
        - Receive augmented GPS signal from CubeSats
        - Determine own position.
- Space Segment role:
    - Receive GPS signals from existing GPS satellites.
    - Augment signal to account for process delay
    - Transmit augmented GPS signal to Earth

Figure 1 presents an overview of the proposed system. The constellation consists of 400 satellites in LEO. These satellites receive the timestamp signals from already existing GPS satellites and slightly modify those signals as if generated by the CubeSat itself. An in-depth analysis will be done during the final paper to determine if this is possible without needing multiple atomic clocks on the mission satellites. The satellites will then broadcast those signals to Earth. Increasing the number of transmitting nodes in the sky will allow for a system with more accurate error-elimination and which is less likely to be critically obstructed from view. A method to accurately capture the mission satellite's positions will be explored in the full paper.

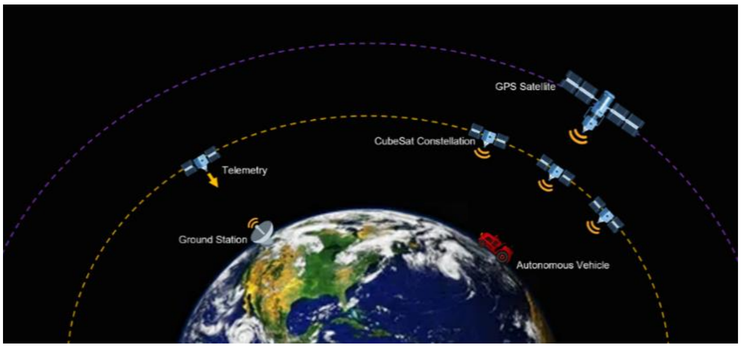

*Figure 1 – Overview of system*

## Key Performance Parameters

1. Standard GPS signals are received at a strength of –125 dBm. To ensure the mission is feasible, signals emitted from the mission satellites have the same or higher strength on Earth.
2. At least two satellites are to be available at all times at all locations between 45 degrees North and South, covering most of the population of Earth.

## **Space Segment Description**.

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## Component Overview:

Table 1 presents the preliminary components chosen to facilitate the satellite mission. The table also presents each component's mass and volume and shows that the satellite can be encased in a 3U satellite structure. Details of each component is found in [4], [5], [6], [7], [8], [9], [10], [11] and [12].

*Table 1 Overview of satellite components*

| Internal | | | | |
|---|---|---|---|---|
| **Subsystem** | **Component Model** | **Supplier** | **Mass (g)** | **Volume (mm)** |
| OBC | Isis On Board Computer | IsiSpace | 94 | 90x96x12 |
| EPS | iEPS Electrical Power System | IsiSpace | 184 | 90x96x27 |
| ADCS | CubeADCS Y-Momentum | CubeSpace | 300 | 90x96x48 |
| Radio-GPS | L-Band Transciever | CubeCom | 90 | 90x96x17 |
| Radio-Comms | Pulsar - VUTRX | ClydeSpace | 100 | 90x96x17 |
| Propulsion | Enpulsion Nano | Enpulsion | 900 | 90x96x83 |
| **Total** | | | **1668** | **90x96x204** |
| **External** | | | | |
| Structure | Zaphod 3U structure | ClydeSpace | 394 | 100x100x340 |
| Solar panels | PHOTON CubeSat Solar Array 3U | ClydeSpace | 540 | NA |
| Antenna-GPS | L-BAND PATCH ANTENNA | TechApp | 170 | 92x92x15 |
| Antenna-Comm | IsiSpace Deployable Antenna | IsiSpace | 100 | 98x98x7 |
| **Total** | | | **1204** | |
| **System Total** | | | **2872** | |

**Development of L-band CubeSat Transceiver**

Since no acceptable CubeSat L-band transceiver could be found to be commercially available, one will be developed according to the specifications similar to the ClydeSpace S-band transceiver [13]. A local South African company, CubeCom, can be contracted for this development.

**Power Budget:**

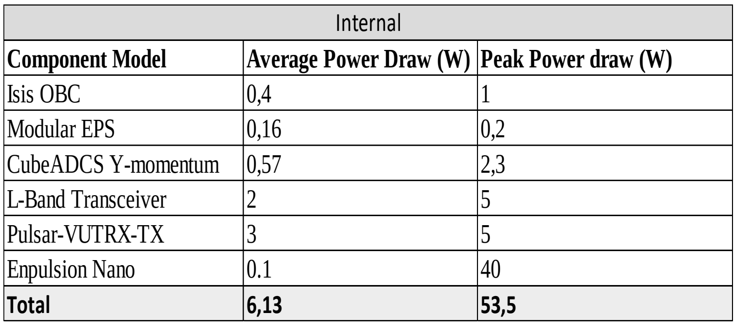
Table 2 presents the average and peak and consumed power of each component on the mission satellite. With this system battery capacity and solar panel package choice can be validated.

The solar panels provided by ClydeSpace offer a maximum power generation of 9W per 3U side populated. [5] By performing a basic power budget analysis, it is estimated that this power generation capacity is sufficient. This fact is compounded by considering dynamically changing loads of power intensive components such as radio transmitter. For example, power can be saved by not providing GPS signals over the ocean and the thruster will be throttled in bursts.

**Link Budget:**

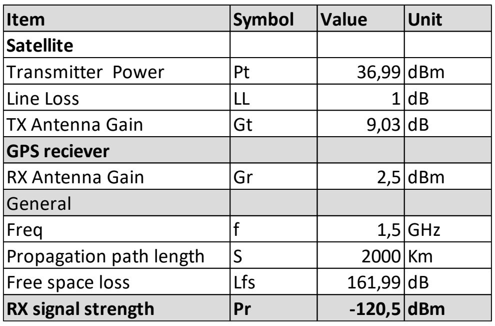
To ensure key parameter 1 the signal received on the ground is required to be –125 dBm or larger to be comparable to standard GPS signals. Table 3 presents a rudimentary link budget, analyzed at a maximum path length of 2000 km and shows that the received signals are in acceptable range.

*Table 2: Power consumption of satellite components*



| Internal | | |
|---|---|---|
| **Component Model** | **Average Power Draw (W)** | **Peak Power draw (W)** |
| Isis OBC | 0,4 | 1 |
| Modular EPS | 0,16 | 0,2 |
| CubeADCS Y-momentum | 0,57 | 2,3 |
| L-Band Transceiver | 2 | 5 |
| Pulsar-VUTRX-TX | 3 | 5 |
| Enpulsion Nano | 0.1 | 40 |
| **Total** | **6,13** | **53,5** |

*Table 3 Satellite Link Budget*



| Item | Symbol | Value | Unit |
|---|---|---|---|
| **Satellite** | | | |
| Transmitter Power | Pt | 36,99 | dBm |
| Line Loss | LL | 1 | dB |
| TX Antenna Gain | Gt | 9,03 | dB |
| **GPS reciever** | | | |
| RX Antenna Gain | Gr | 2,5 | dBm |
| General | | | |
| Freq | f | 1,5 | GHz |
| Propagation path length | S | 2000 | Km |
| Free space loss | Lfs | 161,99 | dB |
| **RX signal strength** | **Pr** | **-120,5** | **dBm** |

**Delta V Budget**

To allow for defective satellites to passively reenter after launch, the constellation is to be launched into a 300x1571 km, 35.05-degree inclined orbit. Most of the Delta-V required will be to raise the perigee from 300 km up to the circular, 1571 km final orbit and drop it back down at End-of-Life to deorbit the satellites. This is estimated to take around 630 m/s. Using the Empulsion Nano FEEP propulsion unit, a specific impulse of 2500 seconds is a conservative estimate of achievable performance, with a propellant mass of 220 g, giving 1950 m/s of available Delta-V. This means 1320 m/s of Delta-V will be available for orbit corrections and collision avoidance maneuvers. Given a single launch of all 400 satellites, without deployment hardware, would mass around 1150 kg, it is reasonable to assume that a commercial launcher will be able to lift this into the intended deployment orbit with much capacity to spare.

**Orbit/Constellation/Description**

To determine the optimal constellation in which to deploy the satellites, the area coverage of each satellite first needs to be calculated. As a first approximation, satellites are assumed to be nadir-pointing and the optimal altitude to place the satellites is the altitude where the signal path length at maximum beam angle is equal to the maximum allowable path length. For the given 67-degree half-power beam angle and 2000 km maximum path length, this altitude works out to be 1571 km. Using the coverage area of each satellite the minimum required number of satellites per orbital plane at this altitude is 19, but an extra satellite is included in each plane as a spare.

A Walker-Delta constellation type is chosen for its good coverage. The inter-plane RAAN angle is calculated such that full coverage is guaranteed by satellites moving in one direction only on the equator, meaning two satellites will always be available between the chosen latitudes of 45 degrees North and South. This gives an orbit inclination of 35.05 degrees needed, and 20 equally spaced planes. The difference in RAAN precession between the deployment orbit and the final orbit is 1.36 degrees per day, meaning satellites can use precession to drift into their respective planes, and then use the difference in period between the deployment and final orbits to establish the correct true anomaly. This process should take around 250 days, with all 400 satellites deployed at once.

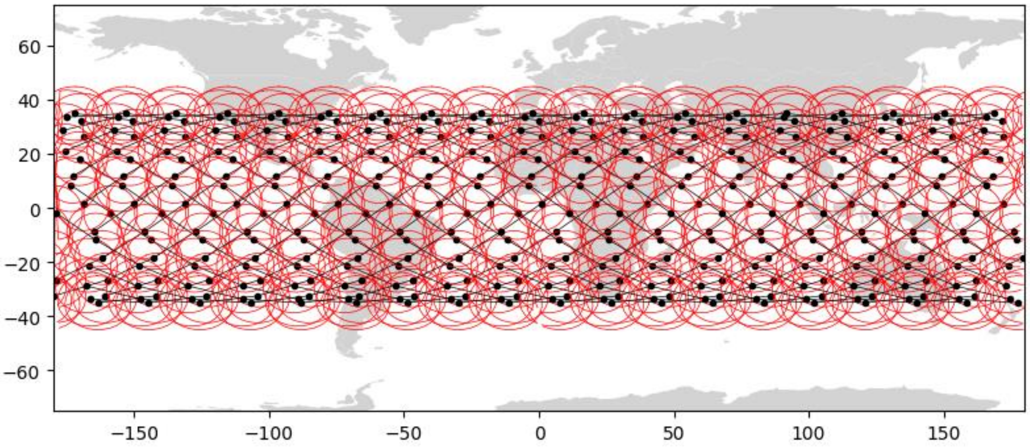


*Figure 2 Coverage of the satellite constellation*

## Implementation Plan

Design and development of the mission can be primarily handled by Stellenbosch University with the support of South African satellite companies. While most satellite components can be obtained locally from these companies or international provider's local branches, assembly of the satellites may have to by contracted out to a facility that has the capabilities to produce an entire satellite constellation. A ground station is already in operation at the university and will be used to communicate with the satellites. Should more communication stations be required, these will be contracted.

Figure 3 presents a satellite conception to launch Gantt chart based on one presented by NASA [14]. Due to the length of the mission, operation and deorbiting it is not included in the chart.

It is proposed that an initial experimental development and launch of a dozen satellites is performed to validate the successful operation of the system. Should the initial satellite group verify mission success, the rest of the constellation can be launched in a single batch and utilize J2 perturbation to precess into the intended orbital shells in roughly 8 months. It is unlikely that such a constellation can be indefinitely maintained by Stellenbosch University, and after the initial experimental launch, it is recommended that the system is either sold or contracted to more suitable agencies.

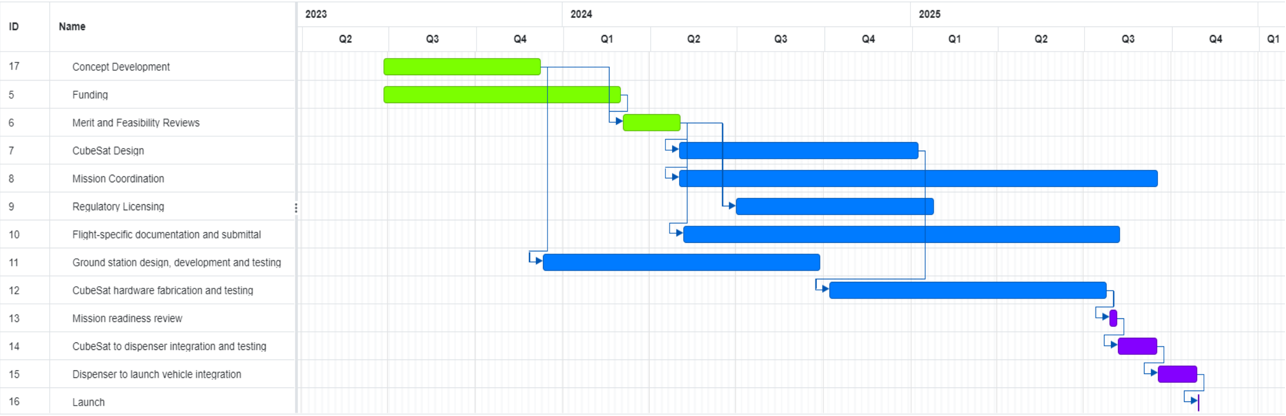


*Figure 3 - Gantt chart of mission development*

Table 4 presents an estimated cost budget of the satellite mission. The costs are split between the cost of satellite components (based on prices found at [15]) and the cost of mission development. Mission development costs are based on five engineers' salaries and the launch costs in [16]. The costs are then expanded for the entire constellation. The final cost of $326 million is deemed within a reasonable range.

*Table 4 – Estimated capital requirement of satellite mission*

| Component | Cost($) | | Development Process | Time (months) | Cost ($) |
|---|---|---|---|---|---|
| Isis On Board Computer | $ 5 100,00 | | Concept Development | 3,00 | $ 167 010,00 |
| iEPS Electrical Power System | $ 4 500,00 | | Securing Funding | 6,00 | $ 334 020,00 |
| CubeADCS Y-Momentum | $ 26 780,00 | | Merit and Feasibility Reviews | 1,50 | $ 83 505,00 |
| L-Band Transciever | $ 7 000,00 | | CubeSat design | 6,00 | $ 334 020,00 |
| Pulsar - VUTRX | $ 6 000,00 | | Mission Coordination | 12,00 | $ 668 040,00 |
| BmP-220 | $ 15 000,00 | | Regulatory Licensing | 5,00 | $ 278 350,00 |
| Zaphod 3U structure | $ 3 900,00 | | Flight-specific documentation | 11,00 | $ 612 370,00 |
| PHOTON CubeSat Solar Array 3U | $ 6 500,00 | | Ground station design | 7,00 | $ 389 690,00 |
| L-BAND PATCH ANTENNA | $ 4 700,00 | | CubeSat hardware | 7,00 | $ 389 690,00 |
| IsiSpace Deployable Antenna | $ 5 000,00 | | Mission readiness review | 0,25 | $ 13 917,50 |
| | | | CubeSat to dispenser | 1,00 | $ 55 670,00 |
| | | | Dispenser to launch vehicle | 1,00 | $ 55 670,00 |
| | | | Launch | 0,10 | $ 300 000,00 |
| | | | Mission operations | 60,00 | $ 334 020,00 |
| | | | Deorbit | 6,00 | $ 33 402,00 |
| Total per satellite: | $ 84 480,00 | | Total | | $ 4 049 374,50 |
| Total for Constallation: | $ 33 792 000,00 | | Total for Constellation | | $ 292 563 082,50 |
| | | | | | |
| Grand Total | $ 326 355 082,50 | | | | |

Major risks to the project are presented in Table 4. The largest risk is the failure to obtain the required funds to develop and maintain the satellite mission. Other risks are mitigated by the size of the satellite constellation, the multiple purposes that these satellites could perform and the fact that these failures will be observed during the first experimental launch.

*Table 5 Major mission risk assessment*

| ID | Risk | Impact | Probability | Risk Score | Effect |
|---|---|---|---|---|---|
| 1 | Failure to obtain needed funds | 5 | 3 | 15 | Mission does not proceed. |
| 2 | System Failure in-orbit | 2 | 5 | 10 | Single satellite failure not major impact on constallation. |
| 3 | Failure to relay GPS signal | 3 | 2 | 6 | Signal not accurate or too weak. Satellite consellation utilized for other means |
| 4 | Failure to increase GPS accuracy | 2 | 3 | 6 | Satellite consellation utilized for other means |
| 5 | Failure to maintain operation | 1 | 5 | 5 | Operation contracted out to more capable organization. |

## References

[1] F. v. D. a. P. Enge, "The World's first GPS MOOC and Worldwide Laboratory using Smartphones," in *roceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Tampa, Florida, 2015.

[2] National Coordination Office for Space-Based Positioning, Navigation, and Timing, "Augmentation Systems," 27 June 2023. [Online]. Available: https://www.gps.gov/systems/augmentations/.

[3] J. R.-P. J. M. T. P. G. N. C. Ordóñez Galán, "Collecting Quality GPS Data in a Canopy Environment," *Analysis of the influence of forest environments on the accuracy of GPS measurements by using genetic algorithms,* vol. 54, no. 7-8, pp. 1829-1834, 2011.

[4] Enpulsion Spacecraft Technology, "Enpulsion nano," 2019. [Online]. Available: hthttps://satsearch.co/products/enpulsion-enpulsion-nano#:~:text=The%20ENPULSION%20NANO%20is%20a%20propulsion%20system%20with,technology%2C%20developed%20under%20ESA%20contracts%20for%2015%20years.. [Accessed 28 June 2023].

[5] ClydeSpace, "AAC_DataSheet_Photon_original.," 27 June 2023. [Online]. Available: https://www.aac-clyde.space/wp-content/uploads/2021/11/AAC_DataSheet_Photon_original.pdf.

[6] ClydeSpace, "AAC_DataSheet_Pulsar_VUTRX-4," 27 June 2023. [Online]. Available: https://www.aac-clyde.space/wp-content/uploads/2021/10/AAC_DataSheet_Pulsar_VUTRX-4.pdf.

[7] ClydeSpace, "AAC_DataSheet_Zaphod," 27 June 2023. [Online]. Available: https://www.aac-clyde.space/wp-content/uploads/2021/11/AAC_DataSheet_Zaphod.pdf.

[8] CubeSpace, "CubeADCS User Manual," 27 June 2023. [Online]. Available: https://www.cubespace.co.za/downloads/cubeadcs_-_user_manual_v3.09_.pdf.

[9] IsiSpace, "ISIS On Board Computer," 27 June 2023. [Online]. Available: https://www.isispace.nl/product/on-board-computer/.

[10] IsiSpace, "ISIS-ANTS-DSH-0001-Antenna_System_Datasheet-04_00," 27 June 2023. [Online]. Available: https://www.isispace.nl/wp-content/uploads/2021/01/ISIS-ANTS-DSH-0001-Antenna_System_Datasheet-04_00.pdf.

[11] IsiSpace, "iEPS Electrical Power System," 27 June 2023. [Online]. Available: https://www.isispace.nl/product/ieps-electrical-power-system/.

[12] TechApp, "https://satsearch.s3.eu-central-1.amazonaws.com/datasheets/satsearch_datasheet_2v8gcl_techapp_consultantes_l_band_antenna.pdf?X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIAJLB7IRZ54RAMS36Q%2F20230629%2Feu-central-

1%2Fs3%2Faws4_request&X-Amz-Date=2," 2023. [Online]. Available: https://satsearch.s3.eu-central-1.amazonaws.com/datasheets/satsearch_datasheet_2v8gcl_techapp_consultantes_l_band_antenna.pdf?X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIAJLB7IRZ54RAMS36Q%2F20230629%2Feu-central-1%2Fs3%2Faws4_request&X-Amz-Date=2. [Accessed 29 June 2023].

[13] ClydeSpace, "Pulsar-STX-S-band-3," 27 June 2023. [Online]. Available: https://www.aac-clyde.space/wp-content/uploads/2021/10/Pulsar-STX-S-band-3.pdf.

[14] National Space Agency, CubeSat101 Basic Concepts and Processes for, San Luis Obispo: California Polytechnic State University, 2017.

[15] EnduroSat, "CubeSat Modules," EnduroSat, 01 January 2023. [Online]. Available: https://www.endurosat.com/products/. [Accessed 29 June 2023].

[16] SatCatalog, "CubeSat Launch Costs," 10 December 2022. [Online]. Available: https://www.satcatalog.com/insights/cubesat-launch-costs/. [Accessed 29 June 2023].