Title: The OuterNet: A novel satellite communication relay constellation

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Need

Satellites need to be controlled from earth to fully utilise their functionality. To do this optimally satellites need the longest and most frequent possible communication access times with their groundstations. Large satellites currently use services such as NASA's Tracking and Data Relay(TDRS) [1], and distributed ground station networks such as SSC's PrioraNet [2]. These services are however very expensive and not available for commercial use. The launch of micro-, nano-, and picosatellites are rapidly increasing among smaller companies and universities [3]. The use of above mentioned TT&C services are not economically feasible for these smaller satellite missions [4]. The only option left for these projects is to build and maintain a small ground station which can amount up to a third of the total mission budget.

Mission Objectives

To address this shortfall the following mission objectives are set:

- Provide a communication opportunity to any satellite in Low Earth Orbit (LEO) at least once each orbit.
- Provide this service to worst-case communication link budget client, namely a 1U CubeSat with VHF/UHF monopole
- The service should be cheaper to use than constructing and maintaining a small ground station over the mission lifetime

Concept of Operations

The project consists of three segments: the space segment, ground segment and user segment. The space segment (OuterNet) consists of 14 satellites evenly spaced in a 900km circular equatorial orbit. The constellation's beam width coverage is such that all LEO satellites in orbits below 600km altitude will come into range of the constellation at least once every orbit (refer to orbit/constellation design for details). When within range, the client satellites can be polled by the constellation to download telemetry and/or upload telecommands.

The ground segment consists of several ground stations spread around the equator. Due to the constellation's equatorial orbit, each of the satellites will pass every ground station during every orbit. Three potential ground stations have already been identified: Guiana Space Centre [5], Broglio Space Centre [6], and Pusat Remote Sensing [7].

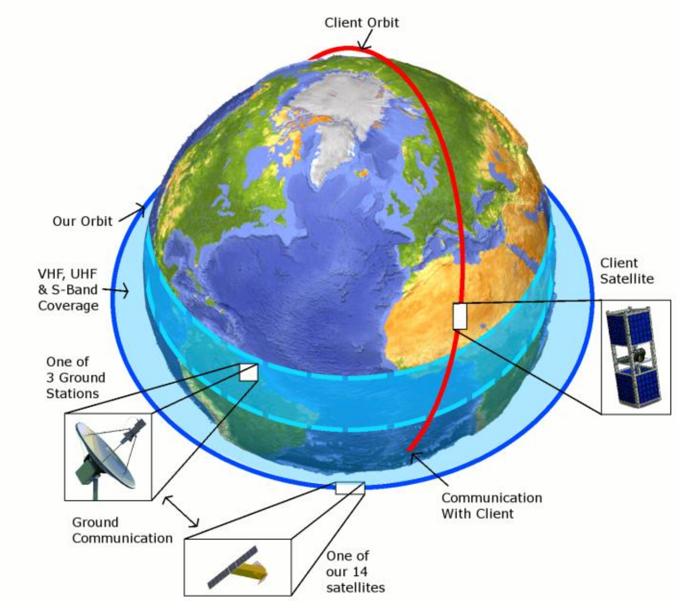


Figure 1: Conceptual illustration of the OuterNet

The user segment consists of clients who register to use the OuterNet service. Pricing will be based on the amount and frequency of data relayed. Satellite operators will be able to configure their TT&C schedules, download telemetry, upload telecommands and configure their communications protocol and modulation technique through a user friendly internet interface.

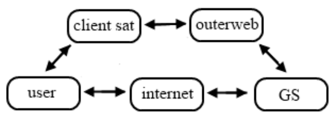


Figure 2: Interfacing between system segments

Key Performance Parameters

The key performance parameters for the proposed mission are:

Communication latency: The time it takes for the client satellite to move into range of the constellation communication footprint. It is dependent on the footprint width on the orbit of the client satellite, which is in turn dependent on the antenna system and number of satellites in the constellation. A target intersection occurrence is once per client satellite orbit.

Communication power: The system must work even if the client satellite has limited communication power. Worst-case client for this parameter is defined as a standard 1-U CubeSat.

Data capacity: Data transferred during a single target intersection occurrence depends on the mean intersection duration and the data rate. The duration depends on the width/area of the communication footprint, which in turn is dependent on the antenna system beam width. A transfer rate of 4800bps will allow for a telemetry packet of about 35kb given a 60-second communication window.

Target orbits: The constellation must supply this service to satellites in orbits ranging from 300km to 800km altitude.

Orbit/Constellation Description

The orbit design of the system consists of calculating the orbital parameters (inclination, eccentricity and semi-major axis) and determining the amount of satellites needed for the constellation. An equatorial orbit is chosen to ensure that the satellites will pass a ground station, which will be situated as close as possible to the equator, at least once per orbit. *Any other orbit would cause the satellite to drift away from the ground station because of the rotation of the earth*. The long latency between communication opportunities between satellites in more inclined orbits (e.g. polar and sun-synchronous) and their ground stations is the problem that our system will improve upon. With the proposed system, client satellites will cross our constellation twice per orbit. There exist areas, at different altitudes, where satellites can slip through without being able to communicate with the constellation. These areas are illustrated in Figure 3.

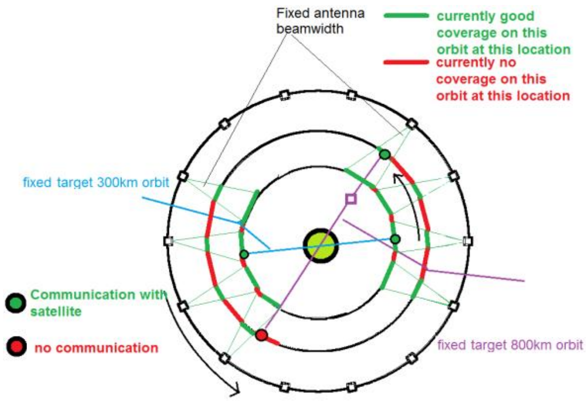


Figure 3: Antenna coverage on different orbits

However, client satellites would never pass through these areas more than once per orbit, ensuring communication at least once per orbit. A passing client satellite will have access time to a satellite in the constellation, which depends on the area of the antenna's beam on the orbital plane of the client satellite. The access time is also influenced by the inclination of the client satellite, which would determine the relative velocities of the two satellites. The system is simulated in MATLAB with the OuterNet at 900 km altitude and the client satellites at various altitudes and inclinations. The resulting average access times are shown in Figure 4. The altitude of 900 km was chosen in order to service a wide range of client satellites at altitudes ranging from 300-800 km, while also keeping the aerodynamic drag force at a minimum. Less drag force results in less orbital station keeping required and therefore less fuel required. Inter-satellite communication can also be considered in the future to minimise the latency between client satellites and a ground station. A message sent from a client satellite to the constellation could then be relayed around the constellation to a constellation satellite that is above (or close to) a ground station, allowing a message to reach earth within minutes.

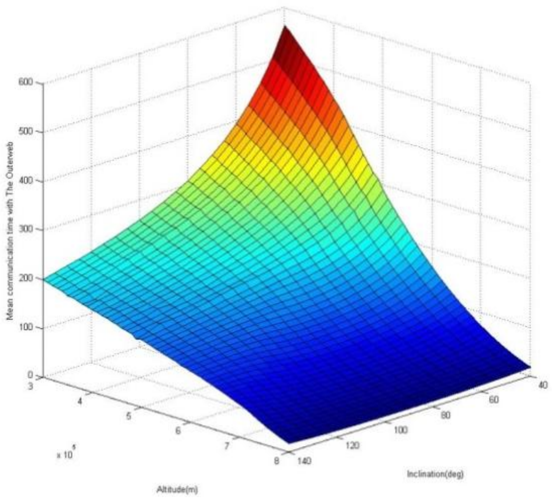


Figure 4: Average access times

Space Segment Description

Link budget

A pointed VHF dipole antenna and a UHF patch antenna array will be used to communicate with client satellites, while an omni-directional dipole will be used to communicate with the ground station. Link budgets were calculated using the *UHF downlink / VHF uplink Full Duplex Transceiver* found on CubeSatShop.com [8] as a worst case client transceiver. The transmitted power of this module is only 150mW. Table 1 shows preliminary parameters of the link budgets with the client satellite and with a ground station.

Table 1: Link Budget

Item	Symbol	Units	Client Uplink	Client DownLink	OuterNet Uplink	OuterNet Downlik
Frequency	f	GHz	0.15	0.45	0.15	0.45
Data rate	R	bps	4800	4800	9200	9200
Bit Error Rate	BER	-	10^{-6}	10^{-6}	10^{-6}	10^{-6}
E_b/N_0	E_b/N_0	dB	10.5(1)	10.5(1)	10.5(1)	10.5(1)
Transmitter power	P_T	Watts	0.06	0.15	0.04	0.12
Transmitter antenna gain	G_T	dB	1	0	7	0
Receiver antenna gain	G_R	dB	0	5.38	0	7
Transmitter feeder loss	L_{FTX}	dB	-1	-1	-0.5	-1
Receiver feeder loss	L_{FRX}	dB	-1	-1	-1	-0.5
Communication Range	R	km	<1200	<1200	<1500	<1500
Free Space Loss	L_{FS}	dB	-136	-145.5	-139.5	-149
Propagation&Polarization loss	L_a	dB	-0.3	-0.3	-0.3	-0.3
Noise Figure	F	-	6	6	6	1
System noise temperature	T_S	K	1154	1154	1154	338

(1) For QPSK modulation according to James R. Wertz and Wiley J. Larson, Space Mission Analysis and Design

The required OuterNet satellite antenna gains and required power were calculated using the following link equation:

$$\frac{E_b}{N_0} = \frac{P_T G_T G_R L_{FS} L_{FRX} L_{FTX} L_a}{k T_s R}$$

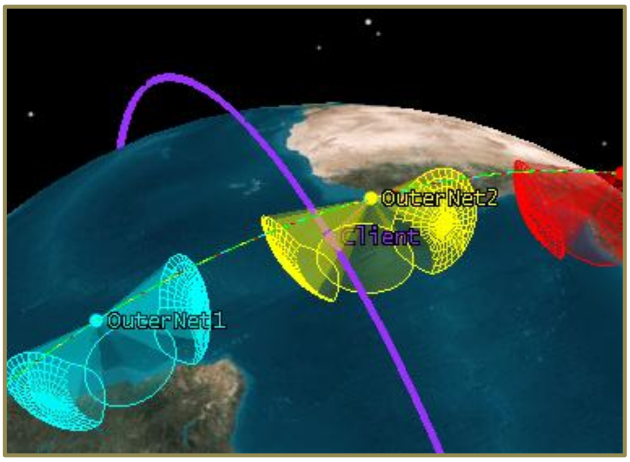


Figure 5: STK simulation of OuterNet commucation footprint

From this analysis it can be seen that the client downlink will require the most power and highest satellite antenna gain, justifying the use of a patch antenna array. The antennas will have a beam width of 60° per antenna spaced out by 22°, producing the pattern shown in Figure 5. Simulation using STK showed that a client satellite with a 600km sun synchronous orbit, gave an average access time of 60 seconds, allowing 35kb data per orbit to be transferred at 4800bps. A pass through the constellations orbit without coverage happened 2 times in 41 passes, and never sequentially. The range limitation was chosen to reduce L_{FS} so that antenna gains would be realizable, while still providing good coverage across the equator. The VHF losses proved to be low enough to allow the use of a low gain dipole antenna. Communication between an OuterNet satellite and a client satellite will be initiated with an ID, sent out by the nearest OuterNet satellite. When the client receives its unique ID, communication between the OuterNet satellite and client satellite will commence. The modulation technique and protocol of the communication system on the OuterNet satellites will be software programmable, in order to accommodate as many client satellites as possible.

Antenna Design

The key performance parameters identify the need for a lot of attention to be given to the design of the antenna system. An antenna beam width of at least 150° in the one direction and 60° in the other direction, as well as sufficient gain, need to be achieved. The use of patch antennas will be

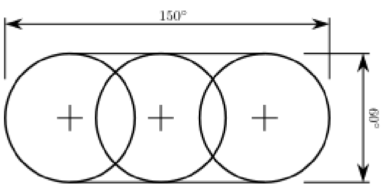


Figure 6: Antenna coverage pattern

preferred above other antennas due to their thin package form. Different patch antennas for different frequencies can be stacked on top of one another to minimise the area required [9]. Initial design points to the use of three patch antennas with a relative angle to produce the 150° beam width. The VHF-band (145MHz) requires a very large patch. Calculations show a patch of minimum length 0.32m, described by: $L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}}$, with c the speed of light, f_0 the resonance frequency, and ε_{reff} the effective dielectric constant [10]. Ceramic has an effective dielectric constant of $\varepsilon_{eff} \approx 10$. The antenna design thus becomes unpractical. A dipole array will probably be used for the VHF-band and patch antennas for the UHF and S-band. Consultation with experts on antenna design confirmed that the antenna specifications are feasible with an antenna array. The final antenna design will be shown in the final document.

Attitude Determination and Control System

The satellites in the constellation will only require pointing the S-band antennas to nadir. A control system is still required to de-tumble the satellite after launch and to keep the satellite 3-axis stabilised at nadir pointing. The proposed altitude of 900km is a bit far for gradient stabilisation and complete magnetic control. The initial ADCS will make use of magnetic de-tumbling and reaction wheels to get 5° pointing accuracy. The sensors to be used are a magnetometer, nadir- and coarse sun sensor combination for the determination of attitude. This can be easily realised using existing off the shelf products to reduce the required development time for these sensors.

Phasing

When the launcher reaches the desired orbit, all the satellites will be released at roughly the same point in the orbit. To achieve the desired ≈25 degree spacing between each satellite, cold gas (butane) thrusters system (Isp of ≈ 70) will need to be designed or bought and intergrated to allow each satellite to enter and exit a phasing orbit. The satellite would need two thruster burns: one at the start of phasing and one at the end of phasing. An example system using this technique is SNAP-1 from SSTL [11]. The phasing of the satellites can confidently be achieved with a cold-gas-thrusters system without adding too much complexity to the satellite design. The thrusters will also allow for the capability to deorbit the satellite at end of life. Mass of fuel needed for delta V burn is [12]:

$$m_P = m_i\left[1 - e^{-\left(\frac{\Delta V}{gIsp}\right)}\right]$$

Table 2: Fuel mass for different satellite mass budgets

Satellite mass	5 kg	10 kg	15 kg
Fuel mass	29 g	58 g	87 g

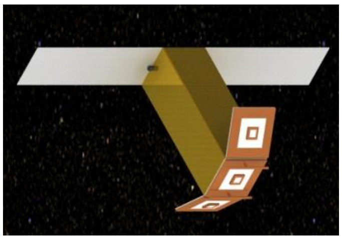
Preliminary Power Budget

The equator eclipse is almost one third of the total orbit period. This requires the satellite to generate maximum energy while in sunlit part of its orbit. Deployable solar panels will be required to increase the collector area while still keeping the bus as small as possible. Solar tracking by these deployable panels is possible while maintaining nadir pointing for the system's main function. Using one fixed panel of 10cmx10cm and two deployed panels of 10cmx30cm the power generation abilities were calculated. The average worst-case orbital power generation for the three panels without tracking is 11.55W and 20.65W for two of the panels tracking the sun. This reveals that tracking solar panels will be definitely advantageous. The satellite's average power use is dependent on the final satellite design, but preliminary results indicate that it will fall well within the available power. A more complete budget will be included in the final document.

Conceptual Design

The physical design of the satellite is mainly driven by the antenna system. The initial conceptual physical design is seen below.

Figure 7: Preliminary Satellite CAD model



Implementation Plan

The system will be operated by a private company as a business venture. Clients can include existing satellite operators who would like to increase the communication time with their satellites, or new satellite operators who cannot afford their own ground stations. The ground infrastructure of the project will consist of one or more ground stations located close to the equator. Possible locations include Kenya, Malaysia and French Guiana. A small staff of technicians can oversee the ground stations. The scheduling and administrative aspects of the program can be performed at operational headquarters. The design and development of the first satellite will cost roughly $2.5M. This includes $62500 for Consumer-off-the-shelf (COTS) parts [13] $1M for labour and $1.25M for the development of a custom communication payload. Thereafter, production of the 14 satellites will cost roughly $75000 each and $750000 total for labour. Launch and integration costs are estimated at $50000 [14]. Operational costs involve the construction and operation of one or more ground stations, and an operational headquarters. The cost of a ground station construction is roughly $125000 and operating it will cost roughly $125000 per year. Operational headquarters, consisting of administrative staff and engineers, will cost roughly $375000 per year. This gives a total life cycle cost of roughly $8.75M for a 5 year program. However, aging satellites can easily be replaced to give the program an infinite lifetime. A basic development schedule is shown in Figure 8

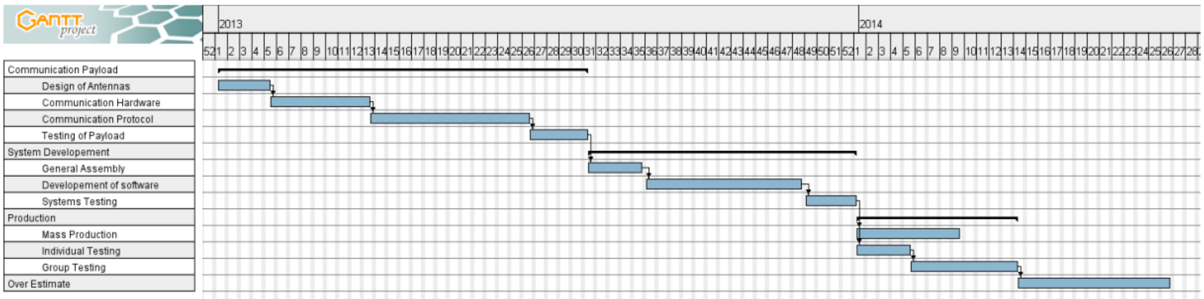


Figure 8: Project GANT chart

The project has several risks which need to be addressed. Firstly, several ground stations need to be acquired in various countries around the equator. Political changes or unrest in these countries could potentially make access to these ground stations difficult. Fortunately, the system will continue to function even with a single ground station. Another risk to any satellite project is losing functionality of a satellite due to solar radiation or hardware malfunction. The loss of a satellite in the constellation will create a blind spot in the equatorial coverage. However, in the event of critical failure the satellite can be replaced. Preliminary calculations on the communication windows and Doppler Effect seem to show that the system is feasible. However, a custom communication payload will have to be designed and tested. There are an increasing number of low-cost satellites being launched by universities and small businesses. The potential client base is continuously growing, mitigating the risk that there will not be enough demand for the services of the constellation. The design team is confident that the project will be a great success.

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