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Bridging the Information Divide: Offering Global Access to Digital Content with a Disruptive CubeSat Constellation

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ABSTRACT

Over half of humanity cannot regularly access the wealth of information available on the Internet. Despite the growth of cellular, cable, and fiber optic networks, a basic level of information and education remains unavailable to billions of people on every continent. Even as smartphones and tablets are seeing larger global adoption, the price of data in most of the world continues to be unaffordable for the majority of global citizens. Nanosatellite constellations have the potential to be a fiscally responsible mechanism for bridging this deepening information divide. The state of the art in maturing technical capabilities, increasing launch opportunities, and achieving commodity costing are enabling a new, investable format for global communication.

This paper presents the Outernet project—a commercially viable nanosatellite communications constellation targeting underserved information consumers throughout the world. Outernet seeks to be the first global, long-term nanosatellite constellation providing a data broadcasting service that is both more desirable and more cost effective than a geosynchronous communications solution.

We present our significant work identifying the key strategic components of a long-view strategy to leverage the continued downward economic forces on the commercialization of space. We review spectrum allocation and the regulatory hurdles surrounding tiny-LEO constellations and present cost-considerations and market comparables pertaining to broadcast data and space-based simple messaging services. Finally, we present examples of user-generated customer premise equipment used to receive and render unencrypted satellite signals.

Most nanosatellite constellations to date have focused on either scientific experimentation or commercialization through imaging services. We conclude that nanosatellite constellations have reached sufficient maturity and cost to become the baseline for a new category of space-based data distribution. Our system-level analysis outlines the path to profitability for any global information delivery system at a cost that is orders of magnitude less than currently available options. Finally, we recommend areas where continued maturation, miniaturization, and commoditization would most beneficially refine the value proposition for these constellations.

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INTRODUCTION

Budgetary challenges and launch access limitations have historically constrained the ability to field new commercial and socially disruptive space capabilities and technologies. Advances over the past decade in highly reliable commercial electronics, miniaturization techniques, and materials have enabled development of a new class of capable, low-cost small "nanosatellites," with system sizes as little as 10x10x10 cm and one kilogram for a fully functional space vehicle (referred to as a single-unit CubeSat). A dramatic trend of increasing secondary and tertiary rideshare launch accommodation opportunities have further motivated the significant value proposition of utilizing these platforms for new, socially disruptive applications. In conjunction, new data protocols, asynchronous communications methods, and maturing schemes for establishing disruption-tolerant networks have been strongly catalyzed by the dramatic increase in demand for timely, accurate global information exchange.

Outernet Overview

Outernet proposes to be a first-of-class broadcast solution uniquely enabled by advances in small satellite engineering. The planned endeavor will utilize a large constellation of nanosatellites, launched via rideshare opportunities, to globally deliver a variety of daily internet media and information content (e.g., wiki pages, RSS feeds, twitter messages, web pages, etc.). The Outernet system will employ a number of new data protocols, asynchronous communications methods, and maturing schemes for establishing disruption-tolerant networks in order to establish a ubiquity of service and minimize barriers to access by users. The Outernet operational concept is illustrated in Figure 1.

Figure 1. The Outernet Operational Concept

The Outernet concept of operations incorporates near-continuous broadcast operations by a large constellation of low-Earth orbiting communications nanosatellites.

Whereas budgetary challenges and launch access limitations have historically constrained the ability to field new commercial and socially disruptive space capabilities and technologies, advances over the past decade in highly reliable commercial electronics, miniaturization techniques, and materials have enabled development of a new class of fully functional, capable systems. A dramatic trend of increasing secondary and tertiary rideshare launch accommodation opportunities have further motivated the significant value proposition of utilizing these platforms for new, socially disruptive applications. In conjunction, new data protocols, asynchronous communications methods, and maturing schemes for establishing disruption-tolerant networks have been strongly catalyzed by the dramatic increase in demand for timely, accurate global information exchange.

The Outernet system will utilize a robust ground network comprised of one or more geographically distributed Mission Management Center(s). The MMC will be used to route daily content updates and scheduling commands to the space segment, with telemetry and provision for a limited amount of return user data, sent back to the Outernet Service Operations Center, where overall system monitoring and management will be performed. User interface to the Outernet service will be made through a simple open-source (DIY) or readily procured, compatible receiver connected to a personal computer of some kind and, potentially, a Wi-Fi router to serve as a local area hotspot.

Project Background

The Media Development Investment Fund (MDIF) has a unique organizational charter which seeks innovative means by which to expand independent media delivery offerings in countries where access may be limited or constrained. To support their investigation and investment in Outernet Inc, Q Space Systems (QSS) was contracted to provide a host of mission engineering and technical consulting services to help realize the concept. In this capacity, QSS assembled a small team of practitioners with a technical bench depth and breadth spanning 70+ years of contributions to more than 20 different space vehicles utilized for a broad array of mission applications around the Earth and throughout the solar system. In addition, QSS partnered with Tolerant Network Solutions (TNS), which provides unique capabilities for developing disruption-tolerant networks across mixed-domain space-terrestrial architectures. QSS led a Phase I feasibility assessment study to examine the proposed Outernet concept and determine the efficacy of building the envisioned broadcast communications architecture utilizing a constellation of low-cost CubeSat form-factor nanosatellite spacecraft. This paper will describe the results of this effort, including a summary of technical findings, performance estimates, and analysis products, as well as pertinent programmatic details for the envisioned system and recommended next steps to realize the disruptive offering.

RF COMMUNICATIONS

Key Constraints and Considerations

The overarching driver on the Outernet RF communications solution is the volume of data to be pushed to users on a daily basis. Given the LEO trade space considered for the constellation, access time to any user on the ground is determined by the number and type of orbit planes, number of spacecraft in the constellation, uniformity of spacecraft spacing, and latitude of the user. In order to take full advantage of the access time when a satellite is "in view" of a ground user, it is desired that the RF broadcast operate with as high a throughput bandwidth as possible while being received by the user over as much of the full satellite pass as possible. The throughput is limited by how high a data rate broadcast can be correctly received given all the space, channel, and ground constraints.

Access Time & Antenna Gain

A significant tradeoff exists between access time and achievable instantaneous throughput, as described below. The access time correlates with the beam width of the antenna on each satellite, and therefore can limit how much antenna gain can be leveraged to increase transmitter Effective Isotropic Radiated Power (EIRP). For a horizon to horizon antenna pattern at the altitudes considered, this indicates a beam that covers roughly 140 degrees (+/-70 deg) about the nadir (Earth-facing) direction. The satellite antenna is therefore limited to a gain value somewhere between -3 dBi and +6 dBi, depending on antenna type (ie.- shaped-beam vs. simple hemispherical pattern), angle between the boresight direction of the antenna and the ground user location, and operational transmit frequency. Similarly, the ground user's antenna should accommodate as much of the in-view access time as possible using either a hemispherical coverage radiation pattern or with a directive pattern in concert with a mechanism that tracks the position of each satellite as it transits the sky.

Ground User Resources

A significant challenge of the main Outernet objective is in achieving successful link closure to global users, having very limited resources of their own. Waveform efficiency and system performance has to be traded against the user expense required to benefit from the

Outernet service. For example, a high-gain tracking ground antenna can achieve a robust high-rate link with the constellation, at the expense of increased complexity and cost. Whereas, a modest bandwidth user link may be established using a low-cost COTS radio product but must account for the associated modest receiver performance achievable and DIY antenna solutions.

System Baseline Configuration

Modes

The baseline Outernet CONOPS provides for a modest rate broadcast to individual ground users as well as a significantly higher rate broadcast to a "hotspot" with a satellite tracking antenna. Individual satellites within the constellation will need to be configured for one or the other broadcast rate according to orbital position. Those configured for low-rate will broadcast at 2 kbps, data consisting of satellite ID, date/time, constellation manifest, RSS, tweets, news, etc. The high-rate broadcast will include the low-rate data, as well as higher bandwidth "static" content, at a data rate on the order of 100 kbps.

Spectrum

The Outernet payload was originally conceptualized and analyzed as an RF communications system that operates in one or more of the global unlicensed Industrial, Scientific, and Medical (ISM) bands (i.e., 27 MHz, 2.45 GHz, or 5.8 GHz). All Outernet user uplink (Payload Rx) and downlink (Payload Tx) signals would therefore need to correspondingly comply with the stipulations for Intentional Radiators specified under FCC Title 47 (Telecommunication) Part 15 (Radio Frequency Devices). FCC regulations on use of the ISM band limit EIRP to +36 dBm (1W RF power, +6 dBi antenna gain), with successive reduction in transmit power required for operation with higher gain antennas. This approach was explored to avoid the lengthy and costly process involved in obtaining an exclusive spectrum license. Therefore, satellites were assumed to receive and broadcast over Unified S-Band (USB) due to the proximity to the traditionally used TT&C band and the available heritage in S-Band radios. However, concerns were identified by both QSS and industry under the RFI, with the availability of compatible low-cost user electronics, probability of link closure, potential for interference, and regulatory uncertainty. As a consequence, the program has been exploring alternate commercial and experimental options in L- and UHF-band. For the purpose of link and system performance analyses, the RF baseline was updated to nominally reflect UHF operations.

Spacecraft Communications Payload

By operating at UHF frequencies, the spacecraft can therefore leverage existing UHF software-defined radio (SDR) and antenna technology designed for Cubesat/smallsat applications. The lower operating frequency means less path loss is incurred by the low-gain antenna to low-gain antenna link. The SDR implementation is projected to be capable of dynamically tuning between feeder and user bands according to orbital location, achieving both link types with a single radio. The SDR would also allow for future waveform upgrades. Satellite communications should be full-duplex in order to accommodate an evolution in service to include scheduled "super–user" uplinks simultaneous with the global broadcast. An alternative half-duplex solution would require careful coordination of "listening" windows when users would be scheduled to uplink and the broadcast halted on a particular satellite platform. The antenna implementation can leverage existing UHF antennas, such as simple crossed-dipole/canted turnstile deployables, compatible with the form factor of a cubesat platform. Higher performing isoflux gain patterns are possible, such as from bifilar/quadrifilar helix antennas, but come at the expense of significant complexity in design and deployment.

Ground Entry Point

By operating at the lower UHF frequencies, user terminal options are opened up to potentially include cheap SDR dongles. SDR software is available open-source on a number of platforms, including Windows, Mac, Linux, and Android and COTS dongles capable of receiving over the UHF band are available for ~$20 over the internet. These SDRs operate from 30 MHz to approximately 1700 MHz, and would also support L-band operations in the quasi-global unlicensed band between 800 and 900 MHz. Broadcasting with straightforward digital modulation (e.g. FSK, BPSK) and FEC coding should further simplify the user-side solution, however some custom software defined radio processing blocks may be required. The user will require an antenna with clear line-of-sight (LOS) to the satellites, which can limit access time depending on location (ie.- in an urban environment). Ideally, the user will be able to obtain or build an antenna with hemispherical coverage of the sky, such as with a quadrifilar helix, however simpler and cheaper back-off options should be evaluated. If the identified spectrum permits multiple channels, it is possible for a ground user to employ more than one SDR dongle to receive broadcast data from two or more satellites simultaneously. The link may also be enhanced through the user of a filter and/or low-noise amplifier ahead of the SDR dongle. The high-rate link will require the user to employ a large high-gain antenna and satellite tracking mount. Aerial antenna rotators and/or amateur telescope mounts may offer relatively inexpensive solutions for the tracker. Tracking also requires additional software to ingest the ephemeris of each satellite in the constellation and continually direct the antenna to the correct point in the sky as each satellite makes a pass of the ground user location. A maximum benefit algorithm must be employed to handle the scenario where more than one satellite is in view of a ground entry point making use of a directional tracking antenna and the entry point must decide which satellite to track.

Broadcast User Link Summary

For an orbital altitude of 700 km, the low-rate broadcast link (2 kbps) can close to an individual user employing a low-gain antenna with nearly 6 dB margin (relative to a bit error rate of 10^{-5}) down to 20 degrees elevation (i.e.- angle above the horizon to the satellite). Margin increases with elevation due to the reduction in effective slant range with higher elevation. However, link performance to a low-cost user terminal should be validated using representative hardware and antennas in a variety of ground environments. In particular, the effectiveness of using an SDR dongle, including noise figure, implementation loss, and the potential for interference from equipment and broadcasts in nearby frequency bands should be evaluated in order to characterize the robustness of the candidate user link. A ground demonstration is recommended to prove the performance of a low-cost user ground terminal, perhaps in conjunction with the leasing of an available orbiting platform with the capability to downlink using representative waveforms and frequencies.

Choice of RF transmitter power depends on the power draw the spacecraft platform can support. With increased transmitter power, comes the ability to close a higher-rate broadcast link for no required change in ground user sensitivity. Furthermore, choice of spacecraft antenna can improve the link in certain geometries, but at the expense of a potentially complex design and deployment mechanism, as discussed above. To demonstrate the trade space including transmitter power and antenna type, a variety of design instantiations are shown in Table 1 below. Radiation patterns for three broad-beam antenna types are assumed: a theoretical omnidirectional antenna, a deployable quadrifilar helix antenna having a shaped-beam pattern concentrating more radiation toward the users at lower elevations that need it most, and a simple yet reliable four-element "turnstyle" antenna with recent cubesat success. Gains are quite modest, as significant directivity would result in narrower ground coverage and therefore less access time for the users. In each case, the same low-gain ground user performance is assumed.

The range of RF transmit powers may be reasonably accommodated by small-to-medium size spacecraft platforms, although the higher powers would likely not be possible from those in the 1U to 3U cubesat class. The achievable data rate (with 3 dB margin) is shown for users at and above 10 degrees, 20 degrees, and 45 degrees elevation. With the higher achievable data rates come reduced access times, as the users would not be capable of receiving the broadcast effectively until the satellites rise to the corresponding minimum elevation angle above the horizon.

The point design of the above link summary corresponds most closely to the turnstyle antenna case with 1.4W RF transmit power. These links assume either Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) modulation with Rate ½ forward error correction (FEC) coding. The required spectral bandwidth for each of these single-channel links is therefore on the order of twice the data rate for QPSK and four times the data rate for BPSK. As such, spectrum availability and channelization can be equally as significant a driver to the ultimate system solution as is the data rate theoretically achievable.

Table 1. Achievable Downlink Data Rates for Different Spacecraft RF Configurations

Tx Power [W]	S/C Antenna	S/C Gain to 10°, 20°, 45° EL [dBi-circular]	EIRP @ 70deg Off-Nadir (to 10deg EL) [dBWi]	Achievable Downlink Data Rate [kbps]		
				≥ 10° EL	≥ 20° EL	≥ 45° EL
1.4	Turnstyle	-3.2, -2.6, -0.3	-3.2	2	3	14
3	Turnstyle	-3.2, -2.6, -0.3	0.1	3	6	30
5	Turnstyle	-3.2, -2.6, -0.3	2.3	5	11	50
8	Turnstyle	-3.2, -2.6, -0.3	4.4	9	17	80
10	Turnstyle	-3.2, -2.6, -0.3	5.3	11	21	100

An enhanced user terminal, or Outernet hotspot, may employ a satellite tracking antenna with higher gain. However, at UHF, the beamwidth will still be relatively broad allowing for fairly coarse pointing accuracy from the gimbal mechanism. A state-of-practice antenna with ~1 m effective aperture, buildable by amateur operators, can support a downlink on the order of 50 kbps to the same elevation and orbit altitude assumed for the low-rate link. This notional terminal benefits from antenna directivity, matched circular polarization, potential RFI filtering, and a low-noise amplifier close to the antenna feed. The same ground entry point SDR could be used with this enhanced front-end to receive at the higher data rate. However, choice of waveform, speed of the specific SDR analog-to-digital hardware and processing blocks, and possible constraints on channelization within the notional UHF band may ultimately constrain the maximum operational downlink rate.

MODELING AND SIMULATION

The modeling and simulation component of the study is associated with studying the geometric and dynamic components of the constellation's motions and interactions with users. This data supports the RF modeling, satellite design, and concept-of-operations. This effort focused on the primary feasibility concerns and engineering trades involved in the constellation design.

Constellation Design

The Outernet constellation is intended to be launched on an ad-hoc basis as secondary rideshare payloads (in launch vehicle parlance) on existing launches in the 2015-2017 timeframe. In this sense, the controllers have limited input over the constellation's deployed configuration. The constellation is defined by which launch opportunities are selected and how many satellites are deployed on each launch. When assessing these inputs, the two primary metrics are average daily access duration, average revisit wait-time, and average daily data downlinked to users on the ground across the globe. In evaluating these metrics, we're interested in long-term average behavior over the globe.

To that end, we initiated the study by evaluating the available launches publically listed by Space Flight Services, then added fidelity and opportunities derived from other resources. Given that the goal of the concept is to offer global daily access, including very high and very low latitudes, some selection of polar or sun-synchronous orbits is desirable. Among these, diversity of right-ascension-of-ascending-node (RAAN) decreases revisit times to terrestrial users. High inclination orbits have low performance near the equator. Although a low inclination (<30^{o}) launch would mitigate this gap, these are typically uncommon—though possible rideshare opportunities on as many as one or two launches per year have been identified within the mission timeframe.

In terms of launch altitude, the largest selection driver is mission lifetime. Given the range of anticipated ballistic coefficients, the target 3 year lifetime specifies a lower altitude limit of roughly 450 km. Adherence to a 25 year deorbit lifetime constrains the upper altitude limit to roughly 700 km. This restriction eliminates many of the available launches. Of the remaining launches, are all circular (or near-circular), inclined orbits.

The predicted launch listing is necessarily vague; many launch parameters are either not known or are proprietary. Typically, only an altitude range and inclination are offered. To evaluate the relevant metrics, we must specify an altitude (within the range) and RAAN, both of which are unknown. (Because the available orbits are circular, argument-of-perigee is not relevant). In an effort to determine the concept's feasibility and assess representative performance for combinations of launch selection, we attempted to model the sensitivity to these values using two approaches: 1. a bounding case and 2. Monte-Carlo analysis. In both cases, we work towards achieving an appropriate level of fidelity, acknowledging the inherent uncertainty. Similarly, for each constellation design, we evaluate two beamwidths: 68^{o}, which covers the full horizon-to-horizon ground-visibility at 600 km, and 20^{o} which is representative of a medium-gain nadir pointing antenna. The corresponding datarates vary according to the transmission antenna gain, and are 10 kbps and 100 kbps respectively.

Bounding Case

For a set of varying high-inclination orbits, we argue that upper limit of constellation performance is associated with the set of RAAN values that most closely resemble a Walker constellation. In this architecture, the orbit planes are spread evenly about the Earth's pole, with alternating orbit-nodes descending and ascending. In addition, the satellites are evenly dispersed in true-anomaly throughout the planes, as would be commanded if the satellites had on-board propulsion. This configuration is illustrated in **Error! Reference source not found.**. Given that the altitude isn't equal for all the orbit planes, no attempt was made to phase the true anomalies between orbits, as is consistent with true Walker constellations. For varying altitudes and inclinations, this configuration will have a limited lifetime, as varying nodal precession will reorient the planes with respect to each other. However, for periods of weeks, it is representative of best-case performance.

The goal of this analysis is to offer best-case results, in order to serve as a design-limiting case. The spacecraft and ground-systems designs must be able to accommodate this upper level of performance, though it is unlikely to be achieved. In addition, this analysis allows us to evaluate competing constellation architectures using a fixed design concept.

Monte-Carlo

Another approach to assess performance in spite of unknown orbit parameters is to use Monte-Carlo methods. In this case, we randomly select orbit RAAN, orbit altitude (within the given range), and satellite true-anomaly. Where the value is drawn from a uniform distribution bounded appropriately, this case is potentially pessimistic, as an informed mission controller would intentionally avoid launching into an orbit with a RAAN that closely matched a previously launch Outernet orbit plane. However, the assumption of a uniformly distributed satellite phasing (true-anomaly) may be optimistic, given that the satellites will initially be deployed from the same point in the orbit. This random phasing could possibly be induced using differential drag or deployment timing/spring variation; the satellites are assumed not to have on-board propulsion.

The goal of this analysis is to simulate enough cases to offer representative performance across varying constellation designs and parameters. In addition, this analysis will help compare different constellation architectures (number of planes and satellites per plane). When comparing architectures, the same random value selections for altitude and RAAN are used for each comparison.

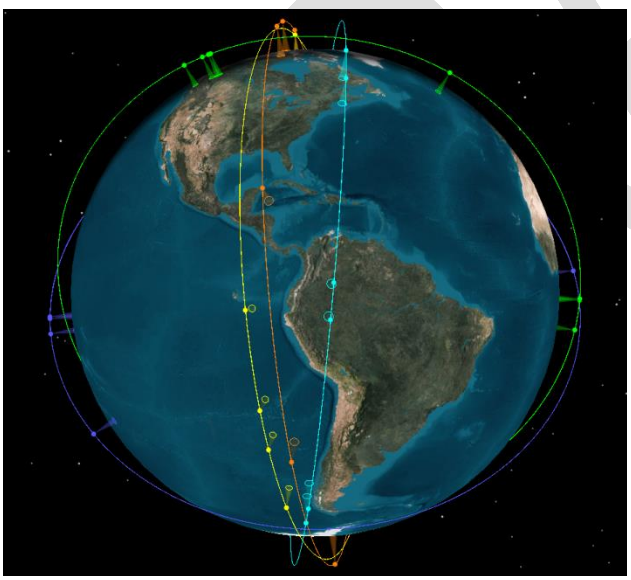

Figure 2. Random (Monte-Carlo) constellation layout. The planes are randomly distributed about the north pole, and the satellites are randomly spaced within each plane.

Results

The results for a wide range of constellation sizes are presented in Figure 3 below, which shows average daily throughput in megabytes (MB). The constellations are given as a number of planes and the number of satellites within that plane. These results are presented for the best-case constellation phasing and orientation. In addition, the ranges of altitudes (as given in the launch options) is considered with a high (H), medium (M), and low (L) case for each constellation configuration. When comparing the equivalent data, which takes into account the beamwidths dependent datarates, the wide beamwidth antenna (68^{o}) is clearly superior to the medium beamwidth (20^{o}) antenna. As expected, larger constellations perform better than smaller constellations, with 8 planes of 20 satellites offering complete coverage to all users above 40^{o} (or below -40^{o}) latitude. The altitude is not a critical parameter in terms of performance.

Generally speaking, the average daily access duration is worst at the equator, and best at high latitudes. When comparing the three constellation options, it appears that the 5x5 constellation is superior at lower latitudes, though only marginally. The difference is likely small enough to attribute to the simulation's finite duration (30 days). There is relatively large variation in the results between the Monte Carlo cases. As seen above, there is relatively small variation between low, medium, and high altitude constellations.

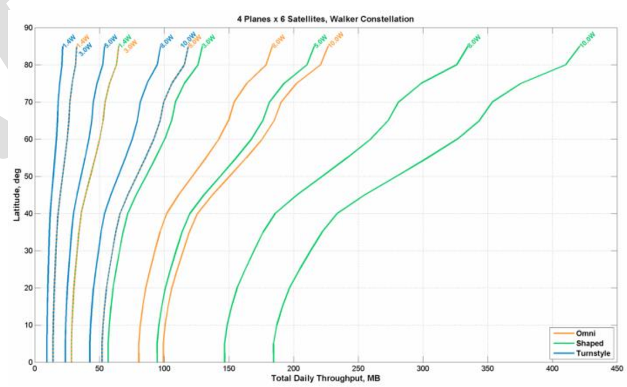

Figure 3. Small constellation (≤25 satellites) average daily throughput for a 4x6 constellation geometry and the analyzed different spacecraft transmit antenna/power configurations.

DATA SERVICES

A variety of techniques exist in practice and in the literature to collect sensing data from constellations and telemeter this information to well-resourced ground systems. Fewer techniques exist for the alternative use of constellations as broadband datacasters. A datacasting constellation being one that is fed by strategic uplink terminals and serves data to multiple, less-resourced ground systems. These systems are particularly advantageous to LEO constellations where their smaller construction and launch costs, ability to wholly own the distribution channel, smaller signal propagation delays, and less required transmit power enable data distribution to small, mobile receive terminals. However, a successfully deployed datacast network must provide a tolerant solution to migrating useful amounts of application data within the transmission footprint despite the disruption-prone link environment.

Disruption-Tolerant Datacasting

A datacast, while not the interactive Internet, disseminates knowledge and geographically targeted humanitarian information. Unidirectional communication links guarantee the anonymity of users as there is no in-band mechanism for tracking who is receiving individual transmissions. With a bulk of the user community passively receiving information, the complexity of the Outernet constellation is reduced, allowing the system to be developed within cost and schedule constraints.

Unlike session-based Internet protocols, datacasts do not have message acknowledgements or retransmission requests. The Outernet constellation relies on stochastic transmission schedules and advanced telecommunications protocols to allow for the patient accumulation of data over time. Delay/Disruption Tolerant Networking (DTN), a technology being standardized by the space agencies of the world, will be used to enable packetized data over Outernet space links. DTN protocols and techniques give an Internet-like data exchange to spacecraft, allowing ground systems to patiently accumulate data over multiple passes, over multiple days, or over multiple weeks without loss due to the occurrence of timeouts, expiring networking sessions, or powering on-and-off the ground terminal.

Data Volume Analysis

Content Types

We define four types of data that can be potentially carried by the Outernet system, which we categorize by temporal relevance and relative data size.

Temporal relevance captures how long data is desirable to the receiving community, implying that once the data has "expired" it may be safely ignored by the user community. Temporal relevance is labelled as either **short** (hours-days) or **long** (days-months). Relative data size measures the size of a particular piece of information relative to other pieces of information transmitted through the Outernet constellation. Size is labelled as either **small** (<300 KB) and **large** (>300 KB). The selection of 300 KB as an inflection point is based on an average size analysis/clustering of Outernet desired content.

Data Sources

We define four data sources: RSS feeds, Wikipedia pages, news websites, and videos. The mapping of these data sources to content types is given in Table 2.

Table 2 - Outernet data content is divided into four categories.

	TEMPORAL RELEVANCE	
	Short	Long
Size: Small	RSS (5KB)	Wiki Pages (100KB)
Size: Large	News Sites (1.4MB)	Videos (237MB)

Simulation Results: Small Constellation Size

We ran simulations using a small constellation of 25 satellites, with a 100kbps data rate and 100% oversampling (i.e. 25x sampling in a 25 satellite constellation). Given these parameters, the overall file delivery results are shown in Figure 4 below.

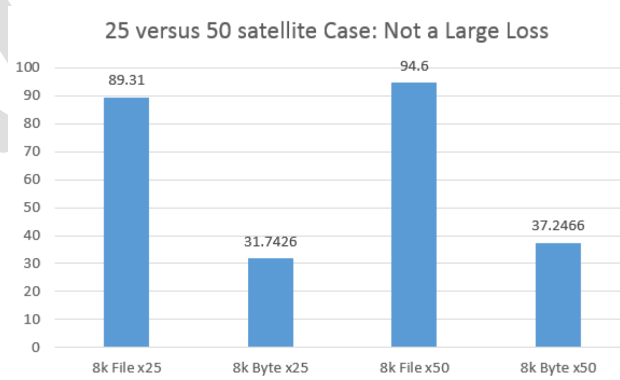

Figure 4 – A constellation size of 25 satellites does not impact performance at this data volume size.

In this figure we see that halving the number of satellites results in only a ~5.3% reduction in files delivered and a ~5.5% reduction in bytes delivered. From this we conclude that 25x oversampling remains a valid option in the constellation, regardless of the number of satellites. For example, given a 50 satellite constellation and 25x sampling, the constellation would be able to hold, for example, two 500MB data volumes.

Simulation Results: Low Data Rate (2kbps)

We ran simulations using a 2kbps data rate and a 2KB packet size for a single day in the 25 satellite constellation and assessed the impact of varying data volumes on delivery rations. At 2kbps, there is simply no opportunity for the constellation to deliver a 500MB data volume. Similarly, very large files such as videos, news, and Wikipedia pages are too large to be received at this data rate. This leaves us only with RSS feeds. To add sensitivity to the low-rate analysis, we define two additional data types: Tweets (size 2500 bytes – full tweet with headers and meta-data) and SMS messages (size 140 bytes). From these three types, we created four data volumes (7MB, 38MB, 23MB, and 10MB) using different numbers of tweets, RSS feeds, and SMS messages. These data volumes are shown in Figure 5 below.

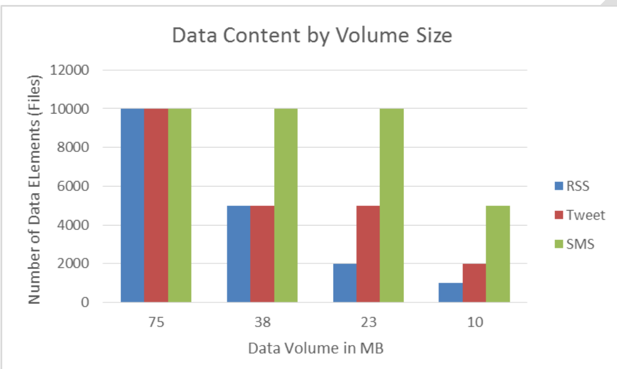

Figure 5 - Lower data rates require a change in the overall user content.

The results of running these data volumes in the simulation for a single day are shown in **Error! Reference source not found.**. In this figure, both percentage of files received and percentage of bytes received are listed. From this figure, we note several significant impacts of running at lower data rates: (1) The benefit of smaller data volumes is not linear, as expected given a constant header size that becomes a larger portion of the data volume as the data volume itself shrinks. This is driven by the content mix comprising the data volume, as seen most dramatically in the small improvement in file delivery between volumes of 38 and 23 MB. (2) With smaller data volumes, a larger percentage of bytes is received. The content mix (i.e., the number of bytes in each file) drives the number of completed files from these bytes. From this, we conclude that the bytes delivered in the system behaves as expected and that the user experience (files delivered not bytes delivered) will be driven by how files themselves are sized.

OUTERNET SYSTEM CONCEPT

Utilizing the envisioned Outernet CONOPS and constellation architecture, along with the results of the analysis activities described in the previous sections, a baseline system concept was created for the space vehicle. The design process was guided by the extensive experience of the QSS project team with developing nanosatellite solutions, along with a strong knowledge of industry offerings. Consistent with the needs of the Outernet mission, the following considerations and specifications were prioritized:

1. Design simplicity paramount. Mass-manufacturable, single-string solution with minimum complexity needed to achieve low recurring unit cost through large scale production (>20).
2. Use flight-proven methods, components, and parts wherever possible, though not necessarily S-class solutions if empirical and/or testing results support viability.
3. Minimum volumetric configuration consistent with the CubeSat standard; non-standard form-factors only permitted for configurations larger than a 6U (six-unit) space vehicle.
4. Compatible with existing (i.e., flight qualified) dispensers/adapters used for low-cost access to space via secondary rideshare.

With these inputs and guidelines, a triple (3U) CubeSat design was conceptualized for the Outernet service. The two principal drivers for the form-factor were the need for capable power generation from four large, deployed solar panels and ample radiator surface area to reject the significant thermal load produced by continuous communications broadcast. While the 3U volume is somewhat more than needed to physically accommodate the requisite space vehicle elements, these two size-driven items could not be adequately implemented in anything less than a 2U volume without exotic and/or costly measures. Given the poor pairing of a 2U space vehicle within a 3U dispenser, it was not considered further. With the 3U design, the spacecraft platform can be configured to provide all the required power, pointing control, on-board processing, and data link necessary to accommodate the Outernet payload (which could also support the spacecraft command and control link) and execute the mission.

INDUSTRY ENGAGEMENT

With the expectation of an eventual acquisition program for the requisite Outernet system elements from industry, QSS utilized the results of the Outernet assessment and definition activities, including the key

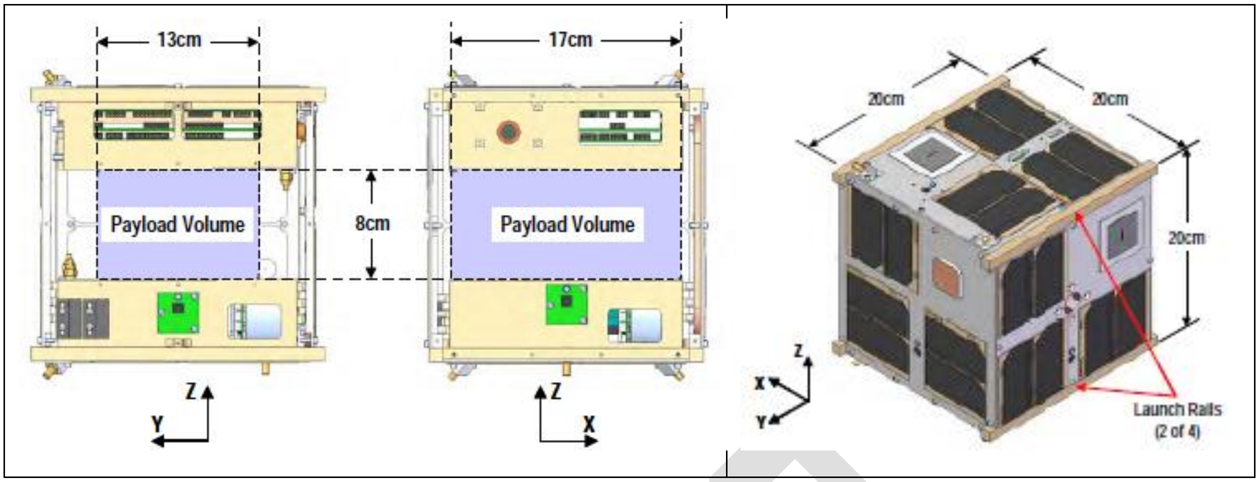

Figure 6. Larger form-factor nanosatellites offer additional hosted payload capacity above what is needed for the Outernet broadcast service [images credit: UTIAS/SFL].

specifications of the baseline space vehicle concept, to engage industry for their review and feedback. With both tactical and strategic objectives in mind, QSS leveraged its deep, global network of organizations with capabilities and offerings related to small satellites. Specifically, providers were sought that had specific expertise with the design, development, and flight delivery of integrated satellite solutions and RF payloads, as well as those offering access to ground station networks and secondary launch services. This due diligence process produced a custom database of more than 50 qualified offerors.

RFI Technical Summary

The majority of respondents provided proposed systems solutions that were, in general, consistent with the internally derived QSS baseline concept. With one exception amongst proffered CubeSat solutions, they utilized a triple (3U) CubeSat spacecraft platform as the basis for their company-specific offering. In several cases, however, larger—flight proven—system designs were proposed. As shown in Figure 6, these configurations were nominally 8-15 kg nanosatellites, equipped with a similar, though more capable build-out of subsystem elements. Whereas the Outernet payload did not require this additional size, mass, or power accommodation, the ample residual capacity of the host platform represented a unique opportunity to consider the possibility of manifesting additional secondary (hosted) payloads that could represent separate revenue streams for Outernet outside the primary broadcast service. The one primary consequence of choosing to utilize a larger, non-standard nanosatellite form-factor is that launch accommodation becomes more limited and/or requiring of custom handling considerations, including the associated adapter hardware, orbit deployment considerations, and overall compatibility with emerging secondary rideshare launch opportunities.

RFI Programmatic Summary

Responders were asked to provide a recommended design that meets the baseline requirements of the included specifications and provide associated ROM costing, incremental funding options, and any proposed alternatives that may afford reductions to overall program cost or schedule. Equally, responders were highly encouraged to propose changes which would reduce development time, risk, and/or cost. For the supplied costing inputs, responders were requested to identify non-recurring engineering (NRE) and recurring engineering (RE) costs, along with a preliminary profile of their funding requirements. QSS received detailed breakdowns of the projected cost to develop all requisite components—in many cases vertically—and in many cases, deliver a complete turn-key integrated solution to orbit by way of direct corporate access or partner-coordinated, secondary rideshare accommodation. With the large objective Outernet constellation size, the RFI responses naturally promoted a consistent overarching design for manufacturing approach in both their supplied narratives and financial data. Given the proprietary nature of the supplied information, QSS is unable to provide specifics of the supplied data, however, offerors did on average, expectedly include a comparatively large upfront proportion of non-recurring engineering (NRE) to develop and prepare for mass-scale production activities to follow.

To assist Outernet planning activities, a high-level project schedule was also requested, with key design, development, and I&T milestones, assuming a start date of July 1, 2014. This aggressive Phase II start date was specifically provided to identify corporate production manufacturing capabilities and facilities that existed now, rather than ones that would need to be developed for the program. Consistent with the programmatic approach to intentionally incorporate some pragmatic NRE for production-scale activities, the average first article delivery was approximately 15 months, with eight for the subsequent unit. Not shown in the table is the implicit, necessary coordination of delivery timelines to support space vehicle integration and testing. The proportional timeline significantly decreased for orders approaching the envisioned 25 units in Phase II.

SUMMARY AND NEXT STEPS

On the basis of these study results—and in particular the findings from the industry engagement under the RFI, it is the determination of QSS that the Outernet concept is not only technically feasible, but its 2015 Phase II execution schedule for preliminary constellation deployment remains viable.

This assertion is based upon the conducted assessments of the constellation architecture, the Outernet user experience, available data bandwidth and frequency constraints, space vehicle packaging options, and current industry solutions. There are, however, several key system components that would benefit from additional maturation, risk reduction, and empirical validation before undertaking full operational system acquisition, that are currently being pursued under a joint Phase IB effort with QSS, TNS, and parallel endeavors undertaken directly by Outernet. The near-term focus is on experiments and validation exercises that will provide tangible risk reduction, technical validation, and performance quantification of the envisioned Outernet system. Among the planned demonstrations will be a series of ground-based tests this summer (July 2014) that will be conducted using Ku-band services.

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