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Communication Link Analysis for a Nanosatellite Constellation in Low Earth Orbit

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Abstract

This paper explores the quality of intersatellite links for a constellation of nanosatellites. In order to characterise satellite performance, the data throughput at various powers, frequencies and antenna gains was calculated and nanosatellite constellations were modelled using Systems Tool Kit (STK). It was found that constant access between a ground station anywhere on Earth and the constellation is possible. It was also found that, depending on the transmission frequency chosen, a nanosatellite constellation can support data rates up to 7.7 Mbps, sufficient for standard definition live video streaming.

Résumé

Ce document vise à examiner la qualité des liaisons intersatellitaires pour une constellation de nanosatellites. Afin de caractériser le rendement d'un satellite, on a calculé le débit des données à diverses puissances, les fréquences et les gains dantenne, puis on a modélisé la constellation de nanosatellites à l'aide du logiciel Systems Tool Kit (STK). On a constaté que laccès constant est possible entre une station au sol située n'importe où sur la Terre et une constellation. De plus, selon la fréquence choisie pour la transmission, une constellation de nanosatellites peut prendre en charge des débits de données allant jusqu'à 7,7 mbps, ce qui est suffisant pour la retransmission vidéo en temps réel de définition standard.

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Executive summary

Communication Link Analysis for a Nanosatellite Constellation in Low Earth Orbit

S. McKenzie-Picot, P. Gavigan; DRDC Ottawa TM 2013-068; Defence Research and Development Canada – Ottawa; August 2013.

Background: This document explores the quality of intersatellite links for a constellation of nanosatellites. It discusses possible satellite constellations, maximum intersatellite data throughput and the effects of Doppler shift, intersatellite and satellite-to-ground contact, ground station requirements and user to user latency.

Principal results: Satellite constellations were modelled in Systems Tool Kit (STK) to find a constellation that provided continuous ground and intersatellite contact. Intersatellite and satellite to ground contact times will be used in the future for networking. Intersatellite data throughput was calculated using both Amplitude Shift Keying (ASK) and Quadrature Phase Shift Keying (QPSK) digital modulation at various frequencies and transmit powers. It was found that a nanosatellite constellation can support data rates of up to 7.7 Mbps, sufficient for standard definition video streaming, when operating at 0.5 GHz on the Ultra High Frequency (UHF) band. Doppler shift caused by satellite relative motion was calculated to be a maximum of +/-120 kHz, occuring at 3 GHz (S-band), which affects the type of digital modulation that can be used.

Ground station requirements were calculated to find required antenna gain and transmit power to communicate with the satellite network. It was found that a ground station requires an antenna with 13.3 dB of gain, and 1.5 W of power, which is small enough to allow the ground station to be portable. User to user latency was calculated for various frequencies, with the latency increasing as packet size and frequency increased.

Future work: Future work will focus on intersatellite networking, with the goal of designing a space-based network that operates without relying on a ground segment as a network link. This work will look at issues arising due to the dynamic nature of an intersatellite network. When completed, this work may simplify space-based communications by potentially allowing constant access to spacecraft. This could also reduce the cost of satellite communications due to the low relative cost of operating nanosatellites compared to traditional spacecraft.

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Communication Link Analysis for a Nanosatellite Constellation in Low Earth Orbit

S. McKenzie-Picot, P. Gavigan ; DRDC Ottawa TM 2013-068 ; Recherche et développement pour la défense Canada – Ottawa ; août 2013.

Contexte : Ce document vise à examiner la qualité des liaisons intersatellitaires pour une constellation de nanosatellites. On y présente la constellation de nanosatellites possible, le débit maximum de données intersatellitaires, les effets du décalage Doppler, les liaisons entre une station au sol et des satellites ou entre des satellites, les exigences des stations au sol et le temps d'attente entre les utilisateurs.

Principaux résultats : La constellation de satellites a été modélisée à l'aide du logiciel Systems Tool Kit (STK) afin de trouver la constellation qui fournissait une liaison continue entre une station au sol et des satellites. Les temps de liaison entre une station au sol et des satellites et entre des satellites eux mêmes seront utilisés dans les futurs travaux de réseautage. Afin de calculer le débit de données intersatellitaires, on a utilisé les outils de modulation par déplacement d'amplitude et de modulation par déplacement de phase à quatre états diverses fréquences et puissances de transmission. On a constaté qu'une constellation de nanosatellites peut prendre en charge des débits de données allant jusqu'à 7,7 mbps, ce qui est suffisant pour la retransmission vidéo en temps réel de définition standard, et ce, lorsqu'on utilise une bande à fréquences ultra-hautes de 0,5 GHz. L'effet Doppler, causé par le mouvement relatif des satellites, a atteint la valeur maximale de +/-120 kHz (avec une bande S de 3 GHz), ce qui a un impact sur le type de modulation numérique qui peut être utilisée.

On a calculé les exigences d'une station au sol afin de trouver les gains d'antenne et la puissance de transmission qui sont requis pour communiquer avec le réseau de satellites. On a constaté qu'une station au sol nécessite un gain d'antenne de 13,3 dB et 1,5 W de puissance, ce qui est suffisant pour permettre à la station au sol d'être portative. Le temps d'attente entre les utilisateurs a été calculé selon diverses fréquences. On a observé que ce temps d'attente augmente au fur et à mesure que la taille du paquet et la fréquence augmentent.

Travaux à venir : Les prochains travaux porteront sur le réseautage intersatellitaire et l'objectif sera de concevoir un réseau basé dans l'espace qui fonctionne sans avoir recours à une station au sol jouant le rôle de liaison de réseau. Dans le cadre de ces travaux, on regardera les questions soulevées par la nature dynamique d'un réseau intersatellitaire. Une fois terminés, ces travaux pourraient simplifier les communications basées dans l'espace en permettant possiblement l'accès contant à l'engin spatial. Ainsi, le cot des communications par satellites pourrait être réduit en raison du faible coût d'exploitation des nanosatellites par rapport aux engins spatiaux traditionnels.

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1 Introduction

This paper examines the communication link quality in a proposed network of nanosatellites with the goal of finding potential satellite constellations and maximum intersatellite and satellite to ground data throughput. The performance of the communications links of this network is characterised in terms of transmit power, frequency, and intersatellite and satellite to ground data rates.

Using Systems Tool Kit (STK), Low Earth Orbit (LEO) constellations were modelled to find a formation that reduced the number of satellites, but still gave constant access in all locations on Earth. This intersatellite network with no fixed ground segments allows for moving ground stations. An analysis of intersatellite and satellite to ground links was completed using the Ultra High Frequency (UHF) band (300 MHz-1 GHz), L-band (1-2 GHz) and S-band (2-3 GHz), to find the power and gain required to transmit and receive data.

To give a performance envelope for the nanosatellites, a minimum performance case and maximum performance case were created. The assumptions used in all calculations are shown in section 3. In section 4, the data throughput in both the minimum and the maximum performance cases is calculated, using both Amplitude Shift Keying (ASK) and Quadrature Phase Shift Keying (QPSK) for digital modulation, and intersatellite contact times are found. Additionally, intersatellite Doppler shifts are calculated and graphed at 0.5 GHz, 1.6 GHz and 3 GHz. In section 5, a ground station analysis is performed to find the power and gain required to communicate to satellites, both in receiving and transmitting conditions. Additionally, four ground stations are created in STK, each at different latitudes, to analyse the satellite to ground contact times. In section 6, the user-to-user latency is calculated to find the time it would take a transmission to be sent between satellites and from satellite to ground. Finally, a summary and conclusion of results is shown in section 7, and sample calculations can be seen in Annex A.

2 Background

Interest in nanosatellites is increasing due to the decreased cost of manufacture and launch [2]. Nanosatellites and other small satellites are small and light enough to be launched as secondary payloads on larger launch vehicles, reducing the cost to reach orbit. Advances in technology have allowed small satellites to perform tasks previously reserved for large satellites, including stellar measurements from space (Canadian Space Agency (CSA)'s Microvariability and Oscillations of Stars (MOST) [3]), and detection and tracking of asteroids and other satellites (Near-Earth Object Surveillance Satellite (NEOSSat), a joint Defence Research and Development Canada (DRDC) and CSA project [4]). Furthermore, University of Toronto Institute for Aerospace Studies (UTIAS)'s nanosatellites, CanX-6, also known as Nanosatellite Tracking Ships (NTS), and AISSat-1 are demonstrating space-based Automatic Identification System (AIS) technologies [5, 6].

Additionally, constellations of nanosatellites are demonstrating their capabilities. The Bright Target Explorer (BRITE) constellation, a joint endeavour between Canada, Austria and Poland is a constellation of six nanosatellites weighing less than 8 kg, which makes highly precise measurements of the brightness variations of stars [2]. The US army is spearheading efforts to provide Intelligence,

Surveillance, and Reconnaissance (ISR) to soldiers through Kestrel Eye, a constellation designed to demonstrate nanosatellite visible imagery technology [7], and DARPA's SeeMe, a planned constellation of two dozen disposable small satellites [8]. In Canada, UTIAS's CanX-4 and CanX-5 are designed to exhibit on-orbit formation flying with relative position measurements accurate to under 10 cm [9].

Using nanosatellites to create a network in space has been discussed, but little documentation is readily available to support such an idea. Potential applications of a network in space include continuous coverage networks (communication or sensed), ISR on demand sensor systems, or Low Data Rate Service (LDRS) networks. Using nanosatellites rather than large satellite buses to create a space-based network would reduce costs, but the limited size and power of nanosatellites means limited data throughput. The purpose of this paper, the beginning of a study of nanosatellite networks, is to look at potential constellations and the maximum data throughput of these nanosatellites.

References to the Iridium and Globalstar constellations are made throughout this paper. To give some background on these constellations, Table 1 outlines some of the constellation properties. While it would be useful for comparison purposes, the authors were unable to find publically available values for satellite power.

Table 1: Iridium and Globalstar Constellations

	Iridium (first generation)	Globalstar (first generation)
Mass (kg)	680 [10]	450 [11]
Number of Active Satellites	66 (6 planes) [12]	40 (5 planes) [12]
Inclination (deg)	86.4 [12]	52 [12]
Orbital Altitude (km)	780 [12]	1410 [12]
Intersatellite Frequency (GHz)	22.55-23.55 [10]	No intersatellite links
Intersatellite Data Rate (Mbps)	25 [10]	N/A
Satellite to Ground Frequency (MHz)	1621.35-1626.5 [12]	1610-1621.35 (user to satellite) 2483.5-2500.0 (satellite to user) [12]
Maximum Customer Data Rate (kbps)	10 [13]	9.6 [14]

3   Assumptions

3.1   Satellites

It was assumed that the nanosatellites in the constellation were built using the Generic Nanosatellite Bus (GNB). The GNB, which can be seen in Figure 1, is UTIAS's 20 cm x 20 cm x 20 cm nanosatellite bus, weighing 7.5 kg, with a payload mass of 2 kg and available payload power of 3 W to 4 W [15].
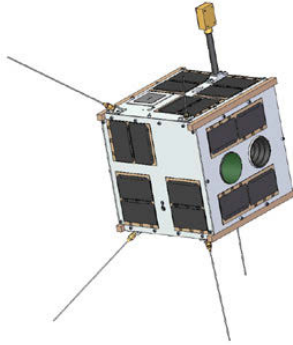
Figure 1: BRITE Nanosatellite, built on UTIAS's GNB [1]

Based on the GNB, the satellites were assumed to have a maximum of 3 W of continuous power available to the payload [15]. It was assumed that the satellites could be configured to operate within the UHF, L and S-bands.

It was assumed that the satellite constellation was made up of planes of satellites in a string-of-pearls configuration (multiple satellites per plane), giving each satellite contact with at least two other satellites at all times, creating a space-based network that is not dependent on ground stations. Details and diagrams of possible constellations are provided in section 4.2.

In order to see a range of results, the satellites were analysed at minimum and maximum ends of the performance envelope. The minimum performance case was assumed to operate at 1.6 GHz, and having 1 W of power and 2 dB of gain. This was assumed to be satellite minimum performance because 1.6 GHz limits the bandwidth when compared to lower frequencies (see section 4.1.2, and because an antenna with 2 dB of gain provides a small amount of amplification to the signal but also has a wide beam (83 degrees, assuming an efficiency of 0.6) requiring little antenna pointing from the satellite [16] (see equations A.1 and A.2 in Annex A). This allows the satellite to be less sophisticated, reducing costs. 1 W was chosen because CanX-2, UTIAS's nanosatellite built on the GNB platform, has a payload power of 1 to 2 W continous [15].

The maximum performance case was assumed to operate at 0.5 GHz and having 3 W of power and 5 dB of gain. This was assumed to be satellite maximum performance because 0.5 GHz offers a larger bandwidth than higher frequencies, allowing higher data throughput, and 3 W is the published GNB continuous payload power [15]. A 5 dB antenna allows more amplification of the signal but the higher gain will cause it to have a narrower beam: a beamwidth of 42 degrees is expected for a parabolic antenna with an efficiency of 0.6 (see equations A.1 and A.2 in Annex A) [16]. Thus, it was assumed that the satellite was capable of pointing the antenna as required. It was assumed that all satellites in the constellation were identical; thus, there is no difference in transmitting and receiving gains.

3.2 Ground Station

The ground station was assumed to be able to point to any angle between 5 and 175 degrees with respect to the horizon, which would allow the ground station to remain in contact with satellites as they approach the horizon. It was assumed to have 13.3 dB gain, which was calculated in section 5.1, and to operate at 1.5 W of power, as discussed in section 5.2.

3.3 Environment and Physical Constraints

It was assumed that background noise temperature, which was used for intersatellite links, was 13 K, that satellite to ground noise temperature was 254 K [17, Chapter 15], and that ground to satellite noise temperature was 30 K in the L-band and 120 K in the UHF band [18, p. 31], which accounts for the worst case scenario of the ground station antenna pointing towards the horizon. This is the worst case scenario because the distance between the satellite and the ground station is at its maximum, and the signal must travel through the thickest portion of the atmosphere. The background space temperature was selected to be 13 K, rather than the typical 5 K seen when pointing into space [19, p. 472] because of the atmosphere present in the low orbital altitudes selected for the constellation, and to compensate for other sources of errors not yet calculated. It was assumed that the signal-to-noise ratio for all transmissions had to be 3 dB, the minimum recommended margin [16], or greater.

The transmission distances were assumed to be the maximum distances between stations. Thus, intersatellite distance was assumed to be 6400 km, which is the linear distance between satellites orbiting at 1000km altitude with 7 satellites in a plane. The satellite to ground distance was assumed to be 3700km, which corresponds to the distance that occurs when a satellite orbiting at 1000km crosses the horizon (see equation A.3 in Annex A).

3.4 Data Transfer

Two cases of data transfer were tested: a small data transfer of 2 kbits and a larger data transfer of 8 Mbits. A data packet of 8 Mbits corresponds to a black and white, 2 km by 2 km image with a resolution of 2 meters/pixel (see equation A.4 in Annex A). For each data transfer, two digital modulations were assumed. ASK was assumed to have a data rate equal to bandwidth/2, and QPSK was assumed to have a data rate equal to bandwidth/0.6 [16].

4 Intersatellite Link Analysis

In the following sections, an analysis of intersatellite links is performed. In section 4.1, selection of transmission frequency bands is outlined. Section 4.2 outlines possible constellation models, and selects one to be used for the remainder of this analysis. Section 4.3 calculates data throughput in the chosen constellation, section 4.4 discusses intersatellite contact times, and section 4.5 shows the Doppler shift caused by the satellites' motion.

4.1 Band Selection

An analysis of satellite links was done in the UHF (300 MHz-1 GHz), L- (1-2 GHz) and S- bands (2-3 GHz). In each range, the power, maximum data rate and antenna length were calculated to show the advantages and disadvantages of each frequency.

4.1.1 UHF Band

The UHF frequencies allow for larger amounts of data to be sent than higher frequency bands using the same transmit power (see Figure 4). However, the lower frequency signal also requires a larger antenna: a parabolic antenna with an efficiency of 0.6 is 1.0 m in diameter for a frequency of 0.5 GHz, which is longer than the GNB bus [15] (see equation A.1 in Annex A). However, other types of antennas with smaller dimensions could be used.

Due to the large data rates available using the UHF band, operation on this band was considered the maximum performance of the satellite: performance was tested at 0.5 GHz, using 3W of power and 5 dB gain.

4.1.2 L-Band

The L-band (1-2 GHz) is commonly used by other communications satellites [12]. Thus, use of the L-band in a nanosatellite constellation could potentially allow the nanosatellites to communicate with larger communications networks such as Iridium, operating between 1621.35 and 1626.5 MHz [12], or Globalstar, operating between 1610 and 1621.35 MHz [12], which would reduce the number of nanosatellites required. As compared to the UHF band, use of the L-band restricts data rates, but requires a smaller antenna: 15 cm diameter, assuming efficiency is 0.6 (see equation A.1 in Annex A). However, data rates on the L-band are more than sufficient for voice transfers.

Due to the smaller available data rates, for this analysis, the L-band was considered to be the low end of the performance envelope. Performance was tested at 1.6 GHz, using 1 W of power and 2 dB gain.

4.1.3 S-Band

The S-band frequencies (2-4 GHz) were considered as they allow the use of a small antenna (8 to 17 cm diameter assuming parabolic) and are commonly allocated for satellite use: Globalstar's downlink operates on the S-band [12], as do geostationary satellite networks Inmarsat and Solaris Mobile [20] among others. However, because an increase in frequency causes a decrease in bandwidth for the same power and transmission distance, the maximum bandwidth a nanosatellite operating with 1 W of power and 2 dB of gain could support is 10.84 kHz (assuming intersatellite distance of 6400 km and noise temperature of 13 K).This corresponds to data rates of 5.42 kbps when using ASK modulation and 18.07 kbps when using QPSK modulation, which is just sufficient for LDRS such as live voice. Using 3 W of power and 5 dB of gain increases the maximum bandwidth to 129.51 kHz, which corresponds to bitrates between 64.76 kbps when using ASK modulation and 215.9 kbps when using QPSK modulation (see equation A.6 in Annex A for bandwidth and data rate calculations).

Thus, operation in the S-band requires a higher-powered satellite bus for any data transfer larger than that required for live voice or small data packets. Because the nanosatellites in this project were modelled based on the GNB, which has limited power, no further analysis, aside from Doppler shift, were performed for the S band. While the GNB bus is normally equiped with an S-band downlink due to the small size of the antenna, this configuration limits data rate [21]. While this small size presents a strong argument for the S-band, interest in the lower frequency bands exists due to higher data throughput. Possible solutions to the larger antennas at lower frequencies include other configurations such as deployable antennas.

4.2 Possible Constellation Configurations

Using STK, constellations were modelled to find a formation that reduced the number of satellites and still gave near-constant access to any location on earth.

4.2.1 Configuration 1: Common Launch Inclinations

Configuration 1, shown in Figure 2, includes three planes of nine satellites each, inclined at 51.6 degrees, orbiting in a circular 500 km orbit (red, orange and yellow in Figure 2). Additionally, it includes three sun-synchronous planes (99.48 degrees (see equation A.9 in Annex A) of seven satellites each, orbiting in a circular 1000 km orbit, for a total of 48 satellites (blues and green in Figure 2). In both the UHF and L-band, this configuration allows essentially continuous coverage for any place on earth, and each satellite has two permanent intersatellite links, with up to nine additional transient ones at any given time.

The inclinations of 51.6 degrees and 99.48 degrees were chosen because these are common launch inclinations [22], making it simple to launch the nanosatellites as secondary payloads on other missions. Launches at 51.6 degrees are provided by Arianespace's Ariane vehicles [22, 23] or Roskosmos's Proton series [22], and sun-synchronous launches are provided by Arianespace's new Vega launch vehicles [23] or Indian Space Research Organisation (ISRO)'s Polar Satellite Launch Vehicle (PSLV) [24]. The altitudes, which fall into the LEO range [25], were again chosen because LEO orbits are common destinations, making launch simpler. Additionally, their low altitudes allow the satellites to operate at lower power settings and still maintain contact with ground stations (see equation A.5 in Annex A for the trade-off of distance and transmit power).

4.2.2 Configuration 2: Polar and Equatorial

Configuration 2, shown in Figure 3, includes four planes of nine sun-synchronous satellites (yellow in Figure 3), and one plane of nine equatorial satellites (green in Figure 3), all in 500 km circular orbits, for a total of 45 satellites. Again, this configuration offers global coverage in both the UHF and L-bands. Each satellite has a minimum of three or four intersatellite links at all times, with up to 13 transient links.
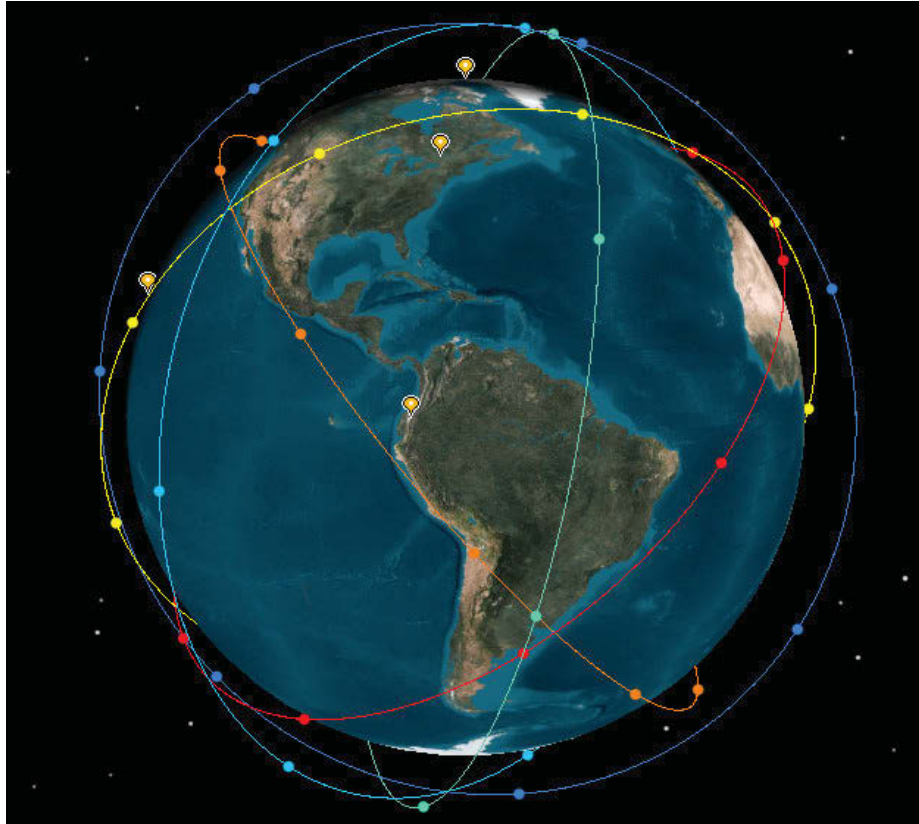
Figure 2: Configuration 1: Commonly Provided Launch Inclinations

4.2.3   Configuration 3: Supplemented with Other Satellite Constellations

Use of existing commercial satellite networks was considered. However, Iridium and Globalstar, both major satellite phone providers, cap their customer data rates at 10 kbps [13] and 9.6 kbps [14] respectively, so offer less data throughput than what could be achieved by launching a constellation of nanosatellites on any of UHF, L or S-bands. Additionally, a customer would need to pay for satellite service to use a commercial network. However, the cost of using a pre-existing commercial constellation could be offset due to the need to launch fewer satellites. This cost analysis is not pursued further in this study, but may be considered in the future.

4.3   Data Throughput in Intersatellite Links

Based on the above configurations, for the purpose of this study, satellites were assumed to operate in configuration 1. Despite the fact that orbit 2 has fewer satellites, orbit 1 was chosen due to the availability of launch inclinations.

For configuration 1, the data throughput in both the minimum (1.6 GHz, 2 dB) and the maximum (0.5 GHz, 5 dB) ends of the performance envelope was calculated. In each case, two versions of digital modulation (ASK and QPSK, at either end of the modulation spectrum) were used to find
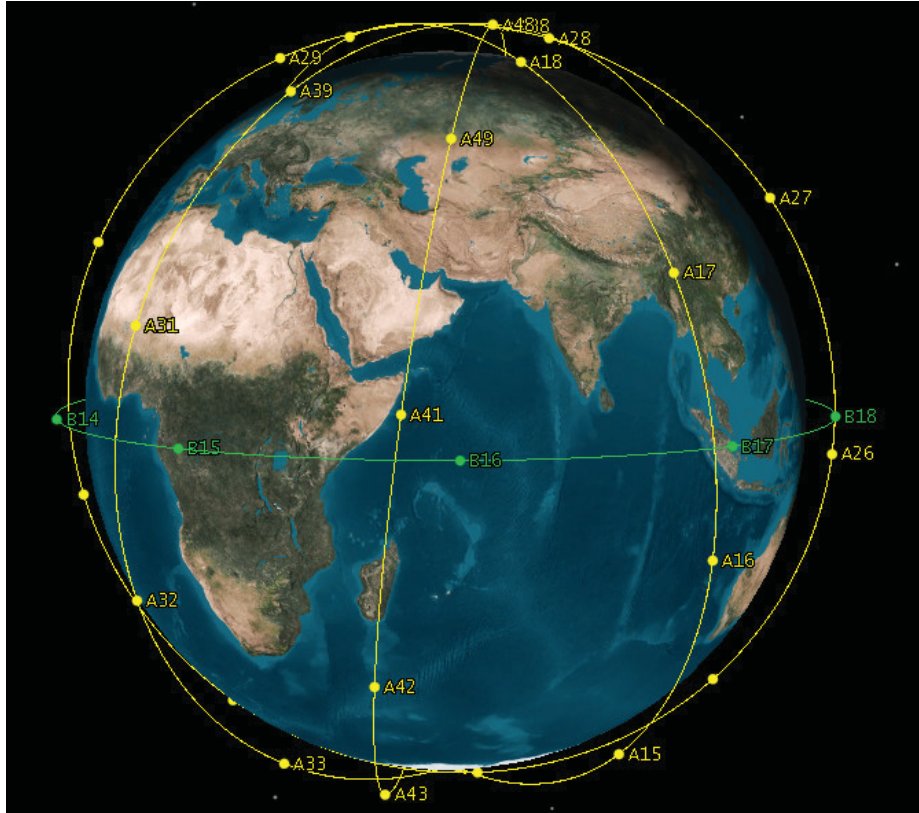
Figure 3: Configuration 2: Polar and Equatoria

the data rate. Thus, four cases were calculated in total: minimum performance ASK, minimum performance QPSK, maximum performance ASK and maximum performance QPSK. These four cases were graphed against transmit power using equation A.6 (see Annex A), and are shown in Figure 4, which shows the maximum intersatellite data rate for a range of power in both the L and UHF bands. The minimum and maximum data rates were tabulated in Table 2.

Table 2 shows that the data rate in the L-band, which represents the minimum performance case, using a minimum power of 1 W, is more than sufficient for voice transfers. At 19 kbps, this is roughly double the maximum customer data rates of Iridium (2.4 kbps voice, 10 kbps internet [13]) and Globalstar (9.6 kbps [14]).

However, larger data transfers would require higher power and larger gain. The UHF band, using 3 W, gives an increased bandwidth, and thus, increases data throughput to nearly 7.7 Mbps when using QPSK modulation, sufficient for standard definition (720 by 480 pixels) video streaming, which requires between 3.6 and 7.0 Mbps depending on the format and compression [26]. While significantly larger than the data rates one could get as a customer on a communications constellation such as Iridium, this is still significantly smaller than Iridium's intersatellite links which operate at 25 Mbps on the K-band [10]. While the proposed arrangement of nanosatellites can produce data rates higher than those available from commercial providers, they lack the power to compete with

the data rates large satellites are capable of.
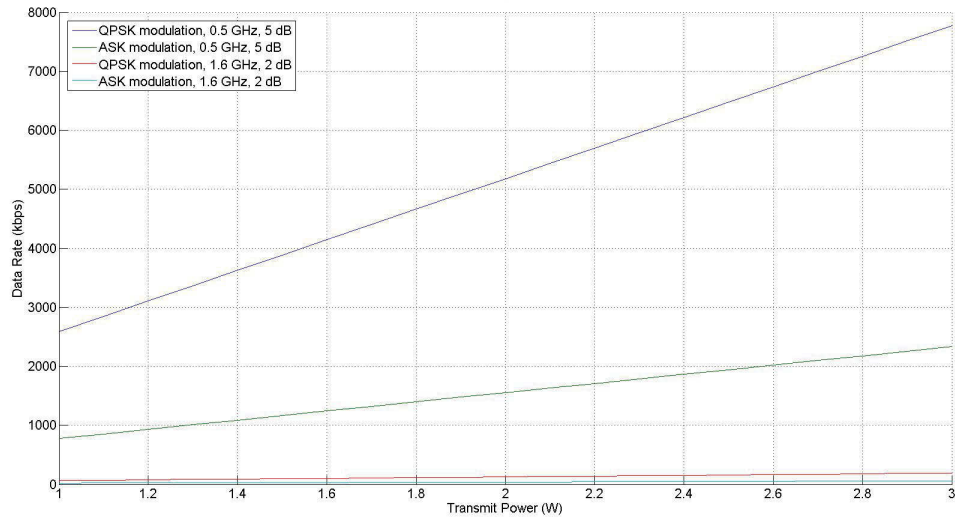
(a) Maximum Intersatellite Data Rate for both Maximum (UHF Band) and Minimum (L-Band) Performance
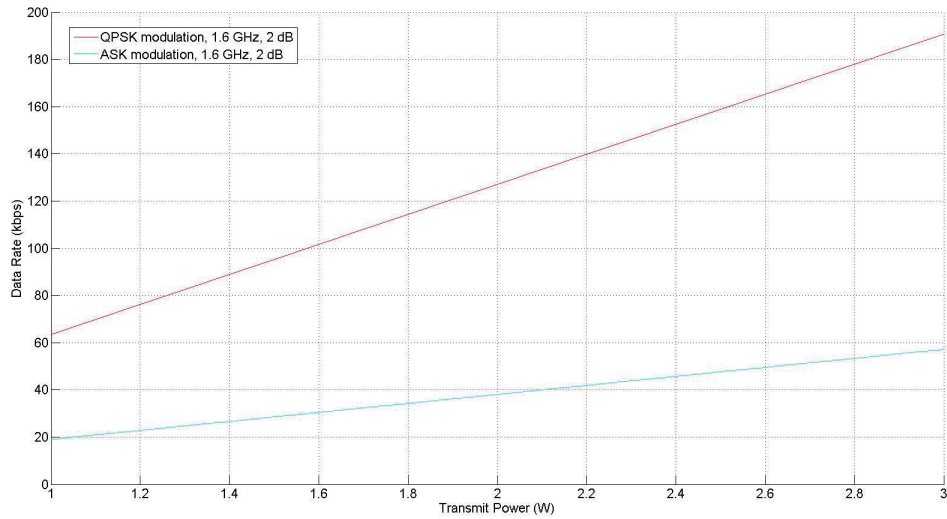
(b) Maximum Intersatellite Data Rate at Minimum (L-Band) Performance

Figure 4: Maximum Intersatellite Data Rate

4.4 Intersatellite Contact Times

In configuration 1, as described above in section 4.2.1, each satellite has two permanent inter-satellite links, with up to nine additional transient links at any given time. Using STK, intersatellite contact times were found. It was found that non-permanent links are typically formed for between 4 and 30 minutes at a time. Using these contact times, Table 3 was created to show the minimum and

Table 2: Maximum Intersatellite Bandwidth

	Minimum Performance	Maximum Performance
Transmitted Power (W)	1	3
Transmitter Gain (dB)	2	5
Receiver Gain (dB)	2	5
Frequency (GHz)	1.6	0.5
Distance (km)	6400	6400
Maximum Bandwidth (kHz)	38.12	4662.5
Data Rate(QPSK) (kbps)	63.54	7770.8
Data Rate (ASK) (kbps)	19.062	2331.2

maximum amount of data that could be sent from one satellite to another, assuming the data rates shown in Table 2 and no delays. These contact times and maximum intersatellite data transfers will be important for intersatellite networking and decisions about how to send larger amounts of data. It will be explored further when networking is explored.

Table 3: Data Throughput Through Satellites

	Minimum Performance		Maximum Performance	
	ASK (Mbits)	QPSK (Mbits)	ASK (Gbits)	QPSK (Gbits)
Min Time (4 min)	4.6	15.2	0.56	1.11
Max Time (30 min)	34.3	114.4	4.20	8.39

4.5 Doppler Effect Analysis

To analyze the Doppler shift caused by the satellites' movement, three different cases were considered: Doppler shift between two satellites in two different planes (different Right Ascension of the Ascending Node (RAAN)) inclined at 51.6 degrees, representing communications between two satellites orbiting at 500 km, Doppler shift between two satellites in two different planes inclined at 99.48 degrees, representing communications between two satellites orbiting at 1000 km and Doppler shift between one satellite at 51.6 degrees and 500 km and one satellite at 99.48 degrees and 1000 km, representing communications between the two different altitudes. These three cases represent typical intersatellite communications. Table 4 shows the orbital elements of satellites used, to show the differences in orbital position of the satellites. Each case was calculated

using equations A.11 and A.12 (Annex A) at three different frequencies: 0.5 GHz, 1.6 GHz and 3 GHz, corresponding to the UHF, L and S-bands.

Table 4: Orbital Elements of Satellites in a Circular Orbit used to Calculate Doppler Shift

Satellite Name	A28	A11	C37	C11
Semi-Major Axis (km)	6871	6871	7371	7371
Inclination (degrees)	51.6	51.6	99.48	99.48
Argument of Periapsis (degrees)	0	0	0	0
RAAN (degrees)	120.0	0	150.0	30.0
True Anomaly (degrees)	293.3	0	342.9	0

As can be seen in Figures 5a to 5c, where the yellow bands indicate the times that the satellites are in contact with each other, Doppler shift increases with increased frequency. Additionally, Doppler shift increases as the distance between the satellites increases. Thus, satellites C37 and C11, which orbit at 1000 km and are 6400 km apart, create a larger Doppler shift than satellites A28 and A11, with their orbital altitude of 500 km and their intersatellite distance of 4700 km, and the largest shifts occur between satellites A11 and C37, which are orbiting at different altitudes.

The maximum shifts, shown in Figure 5b, are less than +/- 30 kHz in the UHF band, and up to +/-120 kHz in the S band and could be handled by a phase-lock loop [27]. However, a larger Doppler shift limits the type of digital modulation that could be used. Frequency Shift Keying (FSK) modulation represents bits by a change of frequency, with one frequency representing one bit (i.e. a binary signal of 1), and a second frequency representing the second bit (i.e. a binary signal of 0) [16]. In order to prevent errors, these frequencies must be distinct. Since a Doppler shift changes the frequency from the original transmitted signal, the modulation must compensate for that. Thus, to prevent bit error when using FSK modulation, the passband representing each bit must be wide enough to include the entire Doppler shift. Therefore, in order to represent two distinct bits, the bandwidth of the transmitted signal must be at least twice the width of the Doppler shift. In the UHF band, with a bandwidth of 4.7 MHz (see Table 2), the shift of +/- 30 kHz poses no problems. In fact, 77 unique passbands could be used. However, in the S band, which has a maximum bandwidth of 141 KHz (see section 4.1.3) and a Doppler shift of up to +/- 120 kHz, or at minimum power in the L-band, which has a maximum bandwidth of 38 kHz and a Doppler shift of +/- 60 kHz, use of FSK is impossible, requiring a different type of modulation to be selected.

5   Ground Station Link Analysis

A ground station analysis was performed to find the power and gain required to communicate to satellites, both in receiving (section 5.1) and transmitting (section 5.2) conditions. Section 5.3 discusses the satellite to ground contact at various places around the world.
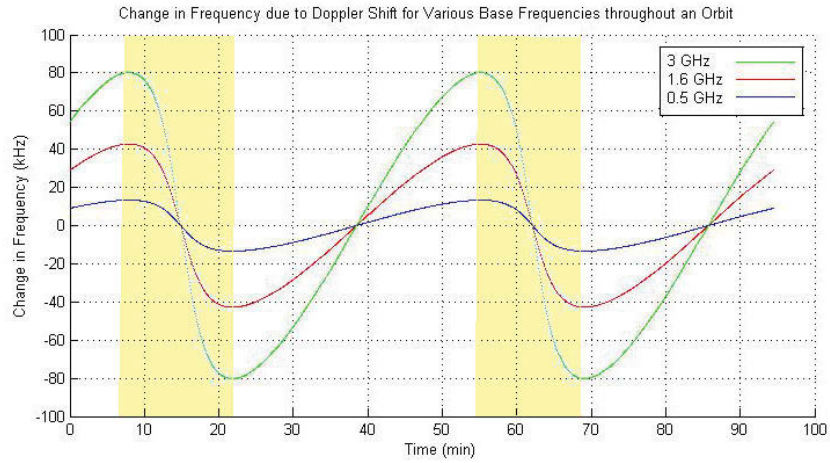
(a) Doppler Shift between Satellites A28 and A11
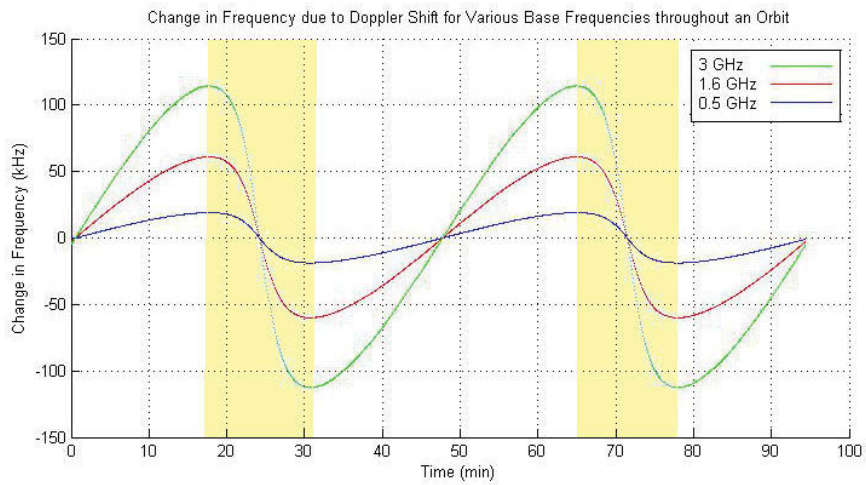
(b) Doppler Shift between Satellites A11 and C37
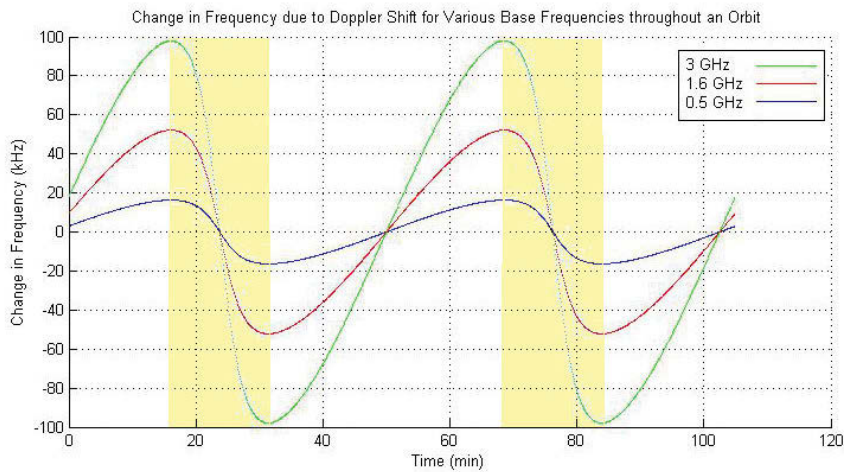
(c) Doppler Shift between Satellites C37 and C11

Figure 5: Doppler Shift between Satellites

5.1 Receiving Gain

To prevent bottlenecks in the network, the ground station must be able receive all the data the satellite is able to transmit. Thus, the ground station must be able to receive a bandwidth of 5.1 MHz, the maximum intersatellite bandwidth (see Table 2 in section 4.3).

The gain of the ground station was calculated using equation A.13, which can be seen in Annex A, assuming the satellite was operating at maximum performance with a transmit power of 3 W, frequency of 0.5 GHz and gain of 5 dB, and that the bandwidth 5.1 MHz, the maximum intersatellite bandwidth (see Table 2). Additionally, the noise temperature on the ground was assumed to be 254K and the transmit distance was assumed to be the distance from the ground station to a satellite orbiting at 1000 km as it crosses the horizon, which is equal to 3700 km. The signal to noise ratio was assumed to be 3 dB.

It was found that the ground station gain must be 13.3 dB or greater to prevent bottlenecks in the network. As with satellite antennas, with lower frequencies, the ground station antenna must increase in size. At 0.5 GHz, assuming the use of a horn antenna with an efficiency of 0.5 (see equation A.14 in Annex A), the ground station antenna must have an area of 1.2 m^2. At 1.6 GHz, this area shrinks to 0.12 m^2.

5.2 Transmitting Power and Gain

Figure 6 shows the minimum ground station power and gain required to transmit to satellites. This figure was graphed using equations A.15 to A.17 (Annex A), which first calculate the noise of the system based on bandwidth and noise temperature, then calculate the required received power from noise and signal to noise ratio. Finally, receiver gain was calculated using the previously calculated received power for a range of transmit powers. In this figure, it was assumed that the ground station was pointing towards the horizon, transmitting to a range of 3700 km, which corresponds to the distance from the ground station to a satellite orbiting at 1000 km as it crosses the horizon, that the noise temperature for that transmission was 90 K, and that a signal to noise ratio of 3 dB was maintained. The gains and frequencies used were the gains and frequencies associated with minimum (2 dB, 1.6 GHz) and maximum (5 dB, 0.5 GHz) performance cases. Finally, the bandwidths used in the calculations (38 kHz on the L-band (1.6 GHz) and 4.7 MHz on the UHF band (0.5 GHz)) are bandwidths that provide the maximum intersatellite data rates at minimum and maximum performance (see table 2 in section 4.3). A ground station able to transmit at the maximum data rate to satellites is using the full potential of the satellite constellation.

If a ground station uses 13.3 dB of gain, it requires only 1.5 W of power to communicate to the satellites. This is the gain required to prevent bottlenecks in the system, as found in the section 5.1.

5.3 Satellite to Ground Contact Times

To analyse the satellite coverage of earth, four ground stations were created in STK, each at different latitudes. The stations, which are indicated by orange placement markers in Figure 2, were located at the geographic North Pole, Kahului, Hawaii (20.88 N, 156.47 W), Ottawa, Canada (45.42 N,
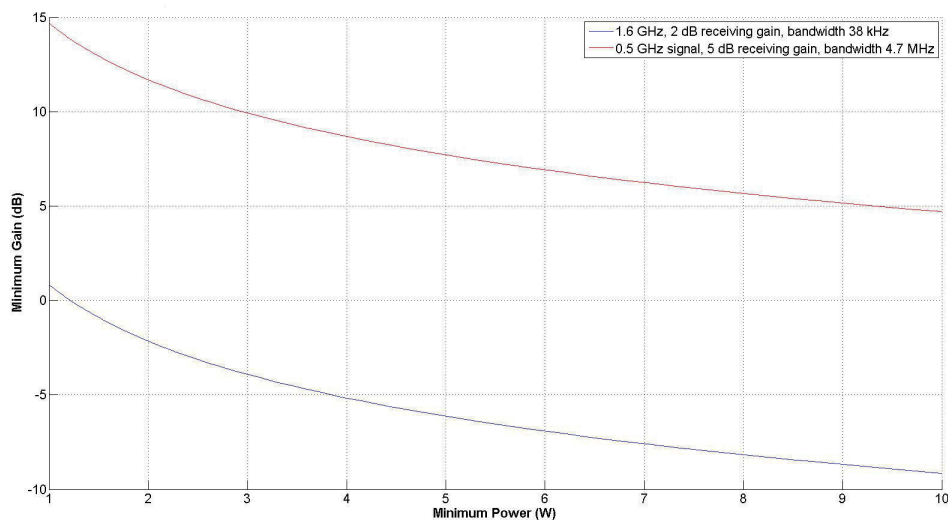
Figure 6: Minimum Ground Station Power and Gain required to Transmit to Satellites orbiting at 1000 km (Range of 3700 km)

75.69 W), and Quito, Ecuador (0.22 S, 78.51 W), selected because the four together cover latitudes from the equator up to the poles. Each of these locations had near-constant contact with at least one satellite, with only a few minutes a day where there was lack of coverage, and it was assumed, due to the range of latitudes of the ground stations, that these results will be seen in any location on Earth. The length of contact with a single specific satellite ranged from three to 13 minutes, depending on location and satellite orbit. These lengths of contact will be used later to design a satellite network and to assess network performance.

6   User to User Latency

Based on configuration 1, described in section 4.2.1, latency from various sources was studied. Transmission latency, the amount of time required to push the entire data packet through the link, was found to be by far the largest contributor to total delay. Processing latency was assumed to be on the order of microseconds, but is dependent on network management and switching techniques, and will be studied in detail in the future. Additionally, queuing latency is dependent on the type of network used but current packet-switching technologies create processing and queuing latencies of around 100 microseconds [10]. Due to the relatively short distances, propagation latency, or the latency due to the distance the signal must travel, is negligible compared to transmission latency: on the order of 20 microseconds.

The figures below show latencies in both the minimum (1.6 GHz and 2 dB gain) and maximum (0.5 GHz and 5 dB of gain) ends of the performance envelope, for a range of power.

As can be seen in Figures 7 and 8, which show the latency between satellites and ground stations,

transmission latency increases with an increase in data packet size or frequency. Thus, sending an 8 Mbit packet from a satellite to the ground at 1.6 GHz and 1 W (minimum performance) takes 3.4 minutes using ASK modulation or 1 minute using QPSK modulation, whereas sending the same data at 0.5 GHz and 3 W (maximum performance) only takes 3 seconds using ASK modulation or 1 second using QPSK modulation. The same pattern holds true for a smaller packet size of 2 kbits, with time delays of up to 0.063 seconds (ASK modulation) or 0.028 seconds (QPSK modulation) at minimum performance and 0.013 seconds at maximum performance (both ASK and QPSK modulation).

Likewise, in Figures 9 and 10, which show intersatellite latency, 8 Mbits of data between two satellites at 1.6 GHz and 1 W (minimum performance) takes 7 minutes using ASK modulation or 2 minutes using QPSK modulation, whereas sending the same data at 0.5 GHz and 3 W (maximum performance) only takes 3 seconds using ASK modulation or 1 second using QPSK modulation. Again, a smaller packet size of 2 kbits has time delays of up to 0.126 seconds (ASK modulation) or 0.053 seconds (QPSK modulation) at minimum performance and 0.022 seconds at maximum performance (both ASK and QPSK modulation).

Transmitting 2 kbits of data at minimum performance takes a minimum of twice as long (ASK modulation) and up to five times (QPSK modulation) as long as it does to send it at maximum performance in both the intersatellite and satellite to ground scenarios. However, the delay is so short that the factor of five would not pose much of a problem: in all cases, the delay is less than 0.4 seconds, which is the upper limit of acceptable for live voice transfers (i.e. satellite phone) [10]. The difference in minimum and maximum performance becomes much more evident when sending larger data packets. When sending 8 Mbits, corresponding to a black and white, 2 km by 2 km image with a resolution of 2 meters/pixel, the minimum performance takes over 60 (up to 130 times for intersatellite links) times as long as sending at maximum performance for both kinds of modulation, indicating that, for larger data transfers, a lower frequency and/or higher power becomes important. Figure 11 shows how decreasing the frequency while keeping the same transmit power the same drastically reduces the transmission latency.

7   Conclusion

A nanosatellite constellation was modelled, and an analysis of satellite links in various frequencies, using various powers and gains, was performed. This link analysis was used to calculate the maximum data throughput between satellites and from satellite to ground. Intersatellite Doppler shift and intersatellite and satellite to ground latency were calculated. Additionally, a set of ground stations were modelled to find the power and gain required to communicate with satellites.

It was found that a constellation of nanosatellites can provide higher data throughput than one could get as a customer on a communications network such as Iridium [13]. At maximum performance, these nanosatellites could stream live video, and minimum performance is more than sufficient for voice.

Additionally, such a constellation creates a space-based network that allows a transmission to be sent without being dependent on ground stations. This intersatellite contact allows ground stations
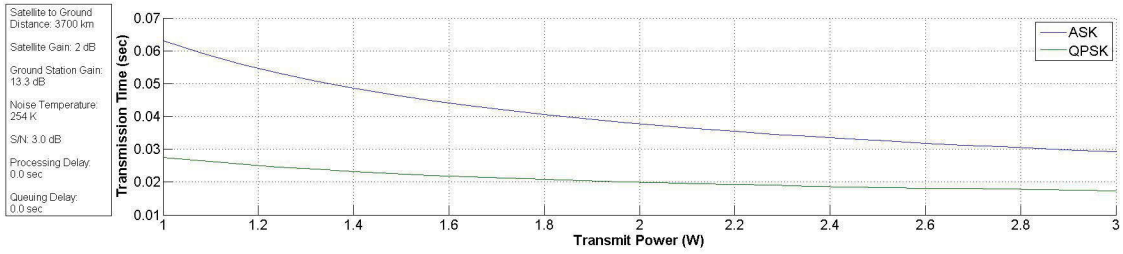
(a) Minimum Performance Transmission Time to send 2 kbits 3700 km from a Satellite to the Ground Station
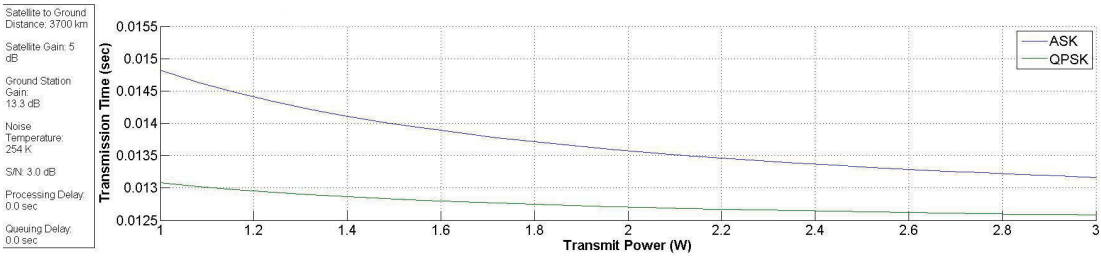
(b) Maximum Performance Transmission Time to send 2kbits 3700 km from a Satellite to the Ground Station

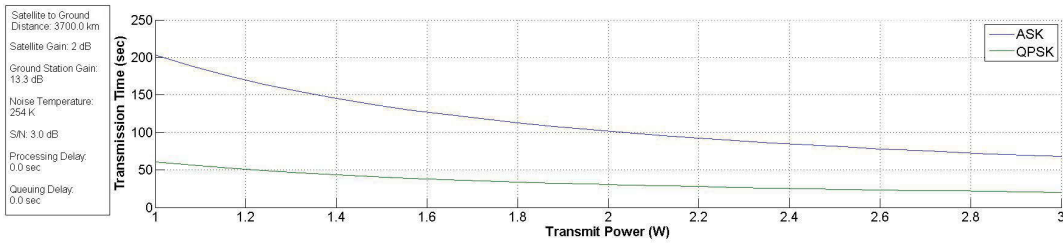Figure 7: Satellite to Ground Latency when Transmitting a 2 kbit Packet

(a) Minimum Performance Transmission Time to send 8Mbits 3700 km from a Satellite to the Ground Station
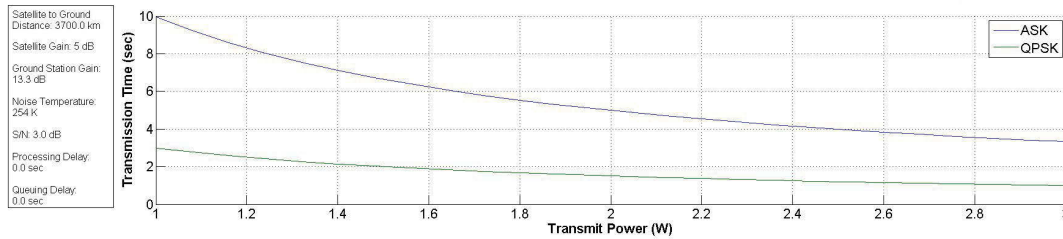
(b) Maximum Performance Transmission Time to send 8Mbits 3700 km from a Satellite to the Ground Station

Figure 8: Satellite to Ground Latency when Transmitting an 8 Mbit Packet
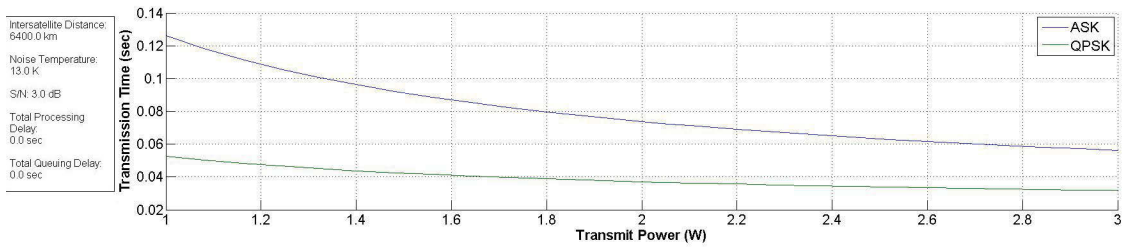
(a) Minimum Performance Intersatellite Transmission Time to Send 2 kbits
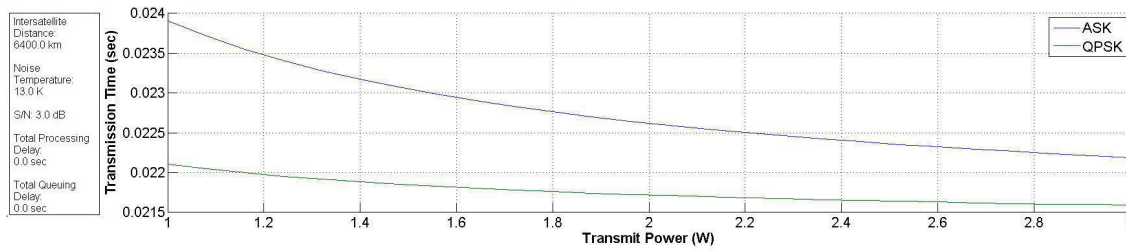
(b) Maximum Performance Intersatellite Transmission Time to Send 2 kbits

Figure 9: Intersatellite Latency when Transmitting a 2 kbit Packet

(a) Minimum Performance Intersatellite Transmission Time to send 8 Mbits

(b) Maximum Performance Intersatellite Transmission Time to send 8 Mbits

Figure 10: Intersatellite Latency when Transmitting an 8 Mbit Packet

Figure 11: Satellite to Ground Latency for various Frequencies and a Set Power of 1 W and a Gain of 2 dB

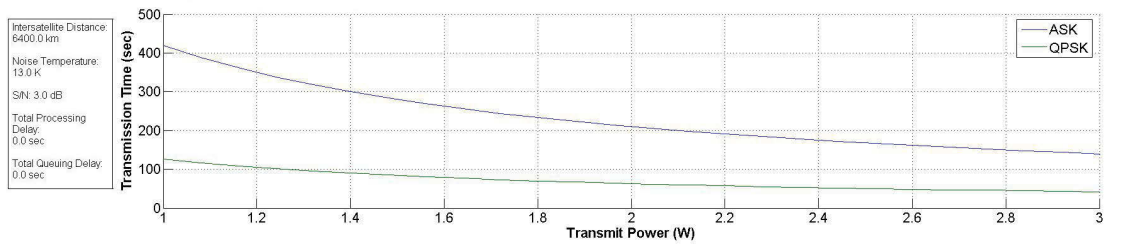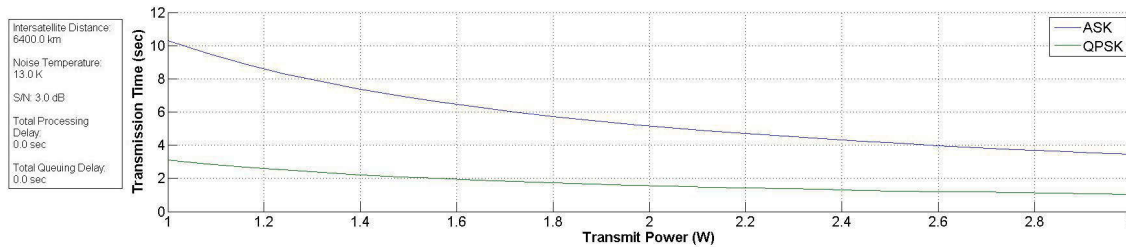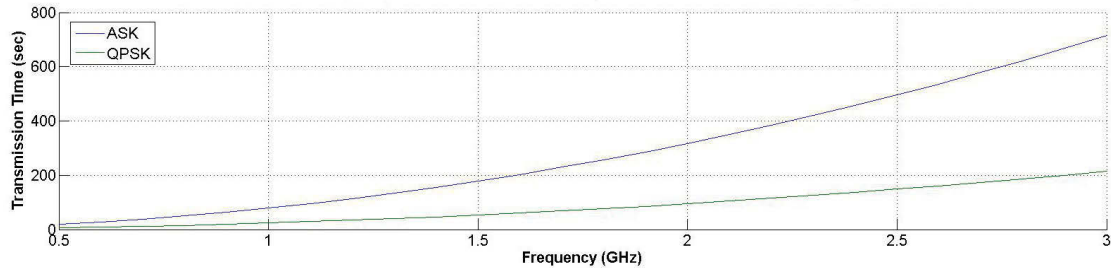to be placed as needed anywhere on Earth, permitting moving ground stations or coverage in places with no ground infrastructure. The constant satellite to ground contact allows the ground station to communicate with the satellites as needed, rather than the brief passes over the ground station seen when operating a single satellite. These ground stations use low levels of power and relatively small antennas, which would allow them to be portable, whether carried by a human or mounted on a vehicle, allowing the potential applications of a nanosatellite constellation to include use in remote areas, or for applications like search and rescue.

8 Future Work

This is an ongoing project. The next step is to look at intersatellite networking, with the goal of designing a space-based network that operates without relying on a ground segment as a network link. While this network will have no fixed ground segments, it will improve ground stations' ability to contact spacecraft due to the number of satellites and the intersatellite communications.

It is expected that issues will arise due to the dynamic nature of the satellite constellation and the small size of the nanosatellites which restricts possible space and power for computers. Satellites will be expected to deal with a constantly changing network, which will challenge the limited computing power of nanosatellites.

Future studies will attempt to present solutions to problems arising from this dynamic network, which will include handling the satellites' limited computing power, dealing with the likelihood of data collisions due to the large number of satellites, and deciding how satellites handle receiving multiple communications at one time. When completed, this work may simplify space-based communications by potentially allowing constant access to spacecraft. This could also reduce the cost of satellite communications due to the low relative cost of operating nanosatellites compared to traditional spacecraft.

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List of Acronyms

AIS Automatic Identification System

ASK Amplitude Shift Keying

BRITE Bright Target Explorer

CSA Canadian Space Agency

DRDC Defence Research and Development Canada

FSK Frequency Shift Keying

GNB Generic Nanosatellite Bus

ISR Intelligence, Surveillance, and Reconnaissance

ISRO Indian Space Research Organisation

LDRS Low Data Rate Service

LEO Low Earth Orbit

MOST Microvariability and Oscillations of Stars

NTS Nanosatellite Tracking Ships

NEOSSat Near-Earth Object Surveillance Satellite

PSLV Polar Satellite Launch Vehicle

QPSK Quadrature Phase Shift Keying

RAAN Right Ascension of the Ascending Node

STK Systems Tool Kit

UHF Ultra High Frequency

UTIAS University of Toronto Institute for Aerospace Studies

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Annex A: Sample Calculations

A.1 Parabolic Antenna Diameter

Equation A.1 below calculates the diameter, D (m), of a parabolic antenna, when given the gain G (dB), wavelength λ (m), and efficiency e. This was rearranged from equations found in [16].

$$D = \left(\frac{10^{G/10} \lambda}{\pi e} \right) \tag{A.1}$$

A.2 Antenna Beamwidth

Equation A.2 calculates the 3 dB beamwidth of a parabolic antenna (*theta*, in degrees), when given the wavelength λ (m) and the diameter, D (m) [16]. [16]

$$\theta = 70 \frac{\lambda}{D} \tag{A.2}$$

A.3 Distance to the Horizon

This equation calculates the distance between a satellite and ground station as the satellite is crossing the horizon, where R is the radius of the planet (km), h is the satellite orbital height (km), and d is the distance between the satellite and ground station (km) [28].

$$d = \sqrt{2Rh + h^2} \tag{A.3}$$

A.4 Image Size

Equation A.4 calculates the size of a black and white image, where r is image resolution (m), w is image width (m), l is image length (m), S is image size (bits), and the multiple of 8 accounts for one channel of 8 bits for a black and white image. For a colour image, multiply by 3 to account for the 3 colour channels.

$$S = \frac{8wl}{r^2} \tag{A.4}$$

A.5 Distance and Power

The equation below calculates the power a station receives, based on the transmit station's power, P_t (W), and the distance d the signal travels (km). G_t (dB) is the gain of the transmit station, G_r (dB) is the gain of the receiving station, λ is the wavelength of the signal (km) and d is the distance between stations (km) [16].

$$P_r = P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{\lambda}{4\pi d} \right)^2 \tag{A.5}$$

A.6 Bandwidth and Data Rate

Used to graph Figure 4, the equations below calculate the bandwidth, B, in Hz, and data rates in bps using ASK (R_{ASK}) and QPSK (R_{QPSK}) modulation, when given transmit power, P_t (W), transmitter gain, G_t (dB), receiver gain G_r (dB), wavelength of the signal, λ (km), distance between stations, d (km), signal to noise ratio, SN (dB), and noise temperature, T (K). k is the Boltzmann constant ($1.381\mathrm{x}10^{-23}$ m^{2}kg/s^{2}K) (equations rearranged from [16]).

$$B = \frac{P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{\lambda}{4\pi d}\right)^2}{10^{(SN/10)} kT} \tag{A.6}$$

$$R_{ASK} = \frac{B}{2} \tag{A.7}$$

$$R_{QPSK} = \frac{B}{0.6} \tag{A.8}$$

A.7 Sun-synchronous Inclination

The equation below, based on [29], calculates the inclination, in radians, required for a sun-synchronous orbit, when given the orbit's semi-major axis, a (km), and eccentricity, e. Here, $\langle\dot{\Omega}\rangle$, the average nodal regression, is $1.992\mathrm{x}10^{-7}$ rad/s (360°/year), R_e, the radius of Earth, is 6378.135 km, μ, the gravitational constant of Earth, is $3.986\mathrm{x}10^5$ km^3/s^2, and J_2, the J$_2$ perturbation coefficient, is $1.083\mathrm{x}10^{-3}$. Inclination can be converted from radians to degrees using equation A.10.

$$i = acos\left(\frac{-2\langle\dot{\Omega}\rangle(1-e^2)^2}{3J_2R_e^2}\sqrt{\frac{a^7}{\mu}}\right) \tag{A.9}$$

$$i = \frac{180i}{\pi} \tag{A.10}$$

A.8 Doppler Shift

Equations A.11 and A.12 were used to graph Figures 5a to 5c. Here, $\vec{v_1}$ and $\vec{v_2}$ are the velocities of each satellite, and $\vec{r_u}$ is the unit vector pointing from the receiver, satellite 2, to the source, satellite 1, at the time of reception. f_0 is the original transmit frequency, f is the Doppler shifted frequency, Δf is the change in frequency caused by the Doppler shift, and c is the speed of light ($3.0\mathrm{x}10^8$ m/s) (adapted from [27, p. 155]).

$$f = f_0\left(\frac{c + \vec{v_1}\cdot\vec{r_u}}{c + \vec{v_2}\cdot\vec{r_u}}\right) \tag{A.11}$$

$$\Delta f = f - f_0 \tag{A.12}$$

A.9 Ground Station Gain

The equation below calculates the required ground station gain (dB) when given satellite transmit power, P_t (W), satellite gain, G_{sat} (dB), noise temperature on the ground, T_{ground} (K), the distance from the satellite to the ground station, d_{ground} (km), the wavelength of the signal, λ (km), the bandwidth of the signal, B (Hz), and signal to noise ratio, SN (dB). Again, k is Boltzmans constant $(1.381\text{x}10^{-23}\ \text{m}^2\text{kg/s}^2\text{K})$. This equation is a specific case of equations A.15 to A.17.

$$G_{ground} = 10 log_{10}\left(\frac{B \times 10^{(SN/10)}kT_{ground}}{P_t 10^{G_{sat}/10}(\frac{\lambda}{4\pi d_{ground}})^2}\right) \tag{A.13}$$

A.10 Horn Antenna Size

The equation below, rearranged from the equation for horn antenna gain found in [30, p. 168], calculates horn antenna aperture size, A, in m^2, given antenna gain, G (dB), antenna efficiency, e, and wavelength of the signal, λ (m).

$$A = \frac{10^{G/10}\lambda^2}{4\pi e} \tag{A.14}$$

A.11 Ground Station Power and Gain

The series of equations below were used to graph ground station gain as a function of power in Figure 6. In equation A.15, N is the noise of the system (W), k is Boltzmans constant $(1.381\text{x}10^{-23}$ $\text{m}^2\text{kg/s}^2\text{K})$, T is the noise temperature (K), and B is bandwidth (Hz). In equation A.16, the received power, P_r (W), is calculated from the signal-to-noise ratio, SN (dB), and in equation A.17, gain, G_r (dB), is calculated from received power, P_r (W), transmitted power, P_t (W), transmitter gain, G_t (dB), wavelength of the signal, λ (km), and distance between the stations, d (km) (equations rearranged from [16]).

$$N = kTB; \tag{A.15}$$

$$P_r = 10^{(SN/10)}N; \tag{A.16}$$

$$G_r = 10 log_{10}\left(\frac{P_r}{P_t 10^{(G_t/10)}(\frac{\lambda}{4\pi d})^2}\right) \tag{A.17}$$

A.12 Transmission Time

The series of equations below were used to graph Figures 7a to 10b. Equation A.18 calculates propegation latency, Lat_{Pr} (s), when given transmission distance, r (m), using the speed of light, c $(3.0\text{x}10^8$ m/s), as the transmission speed [10].

$$Lat_{Pr} = \frac{r}{c} \tag{A.18}$$

Equation A.19 calculates the bandwidth, B, in Hz, when given transmit power, P_t (W), transmitter gain, G_t (dB), receiver gain, G_r (dB), the wavelength of the signal, λ (km), distance between the stations, d (km), signal to noise ratio, SN (dB), and noise temperature, T (K). Again, k is Boltzmans constant (1.381×10^{-23} m^{2}kg/s^{2}K) (equations rearranged from [16]).

$$B = \frac{P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{\lambda}{4\pi d}\right)^2}{10^{(SN/10)} kT} \tag{A.19}$$

Equation A.20 calculates transmission latency, Lat_{Tr} (s), when given the size of the packet to be transmitted ($size$, in bits), and the data rate, R (bps) [10].

$$Lat_{Tr} = \frac{size}{R} \tag{A.20}$$

Equations A.21 and A.22 calculate total user to user latency (s), for different types of digital modulation (ASK and QPSK). In these equations, Lat_{Pc} is the processing delay (s), a constant dependant on the computer on board the satellite, and Lat_{Qu} is the queuing delay (s), again a constant dependant on the satellite. Here, transmission latency, shown in A.20, was recalculated as a function of bandwidth, B (Hz), using relationships found in equations A.7 and A.8, and then as a function of power, using equation A.6.

$$t_{ASK} = Lat_{Pr} + Lat_{Pc} + Lat_{Qu} + \left(\frac{2 size (10^{(SN/10)} kT)}{P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{\lambda}{4\pi d}\right)^2} \right) \tag{A.21}$$

$$t_{QPSK} = Lat_{Pr} + Lat_{Pc} + Lat_{Qu} + \left(\frac{0.6 size (10^{(SN/10)} kT)}{P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{\lambda}{4\pi d}\right)^2} \right) \tag{A.22}$$

A.13   Transmission Time as a Function of Frequency

Figure 11 was graphed using equations A.23 and A.24, which were found by replacing wavelength (λ) with c/f, where c is the speed of light (3.0×10^5 km/s) and f is the frequency of the signal (Hz).

$$t_{ASK} = Lat_{Pr} + Lat_{Pc} + Lat_{Qu} + \left(\frac{2 size (10^{(SN/10)} kT)}{P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{c/f}{4\pi d}\right)^2} \right) \tag{A.23}$$

$$t_{QPSK} = Lat_{Pr} + Lat_{Pc} + Lat_{Qu} + \left(\frac{0.6 size (10^{(SN/10)} kT)}{P_t 10^{(G_t/10)} 10^{(G_r/10)} \left(\frac{c/f}{4\pi d}\right)^2} \right) \tag{A.24}$$

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This paper explores the quality of intersatellite links for a constellation of nanosatellites. In order to characterise satellite performance, the data throughput at various powers, frequencies and antenna gains was calculated and nanosatellite constellations were modelled using STK. It was found that constant access between a ground station anywhere on Earth and the constellation is possible. It was also found that, depending on the transmission frequency chosen, a nanosatellite constellation can support data rates up to 7.7 Mbps, sufficient for standard definition live video streaming.

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