IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 25, 2016, accepted September 11, 2016, date of publication September 13, 2016, date of current version January 27, 2017.

Digital Object Identifier 10.1109/ACCESS.2016.2608929

Systems Engineering of a Terabit Elliptic Orbit Satellite and Phased Array Ground Station for IoT Connectivity and Consumer Internet Access

RICK L. STURDIVANT[1], (Member, IEEE), AND EDWIN K. P. CHONG[2], (Fellow, IEEE)
[1]Microwave Products and Technology, Inc., Fullerton, CA 92831, USA
[2]Electrical and Computer Engineering Department and the Mathematics Department, Colorado State University, Fort Collins, CO 80523, USA
Corresponding author: R. L. Sturdivant (ricksturdivant@gmail.com)

ABSTRACT Systems engineering of a satellite based data communication baseline concept is presented to achieve terabit per second throughput. It uses a constellation of five Molniya satellites and one dimension electronic scanning phased array ground terminals. The result is a baseline concept that meets customer needs for internet of things (IoT) data connectivity and for consumer high data rate internet access. Molniya orbit satellites provide the benefits of available bandwidth, lack of interference with other satellite links, and less crowded orbital paths. A drawback is that they are not geostationary since they have highly elliptical orbits. This requires ground station terminals with the ability track the satellites as they pass overhead during their orbit. However, since Molniya satellites with a properly selected eccentricity pass along the same path at nearly constant elevations relative to a fixed position on the Earth, simple and low-cost single axis scanning antennas can be used for the consumer ground terminal. This is a distinct advantage compared with competing low earth orbit constellations. The proposed solution leverages advances in semiconductor technology and low-cost antenna laminate substrate materials for an affordable phased array tracking ground terminal antenna. This paper presents link budget trade studies, system concept, orbital dynamics simulation results, and ground station component trade study.

INDEX TERMS Satellite, GEO, LEO, Molniya, orbit, internet of things, IoT, rural internet.

I. INTRODUCTION

The desire high data rates for users and machines continue to increase. Providing access to these users and machines is a growing concern and opportunity. One possible solution is to use satellites to provide connectivity access which is why high-throughput satellites (HTS) are being considered. Most of the solutions considered so far are based on low earth orbit (LEO) or geostationary (GEO) satellite systems. This work performs systems engineering of a baseline concepts for an alternative system based upon elliptic orbit satellites such as Molniya or low apogee elliptic virtual geo orbit satellites.

Molniya orbits are one type of elliptical orbit and have been used in Russian television broadcasting for many decades. In fact, the word Molniya is Russian for ‘lightning’ which refers to the speed at which the satellites travels at perigee. The approach of using Molniya satellites and single axis scanning antennas has been investigated by others. For instance, it was proposed by the late W.T. (Bill) Brandon who found that if the Molniya orbit satellites use an eccentricity near 0.722, then they will follow nearly the same ground track in a north-south path at medium to high latitudes as described in [1] and [2]. This approach was also proposed in [3] and [4]. A similar approach, but with much lower apogee elliptical orbits, was proposed in [5]. A good summary of various elliptic orbit satellites is provided in [6] and [7].

However, these prior investigations suffer from four important limitations. First, prior work does mention single axis ground stations [1], [5], but they do not present a viable concept for a low cost consumer ground station which is an important step in the systems engineering of a complete solution. This is a limitation because a complete system solution is required which includes the satellite *and* ground station. This limitation was certainly due to the fact the necessary technology was not available nor on the horizon at the time these prior systems were proposed. Second, the prior investigations did not analyze the variation in the Molniya orbit as viewed from the single axis ground station which is critical since it directly affects the requirements of the ground station antenna. Instead the prior workers focused on analysis of the ground track path of the satellites which is important, but does not address the pointing requirement for the ground station. Third, the prior investigations do not discuss implications from the link budget on the requirements for the consumer ground station. That is, the prior efforts in this area did not perform the analysis demonstrating how system level link budget requirements impact the requirements for the consumer ground terminal. This is an important limitation in the prior work since demonstrating a baseline link budget and translating it to the subsystem requirements is critical for a viable baseline concept. Fourth, they do not address the systems engineering of HTS using elliptic orbit satellites in any meaningful fashion This work addresses these limitations.

This work is distinct from other prior work and is significant in the following ways.

First, a systems engineering baseline is described using elliptic orbit satellites and low cost single axis ground stations in sufficient detail to show feasibility. To the knowledge of the authors, a system level baseline solution with Molniya satellites and a viable consumer ground station as a complete system has not been presented as a HTS solution.

Second, the needs analysis includes the opportunity motivators, customer market analysis, and financial viability of the solution in the context of the system design which is a new contribution. It is significant since the baseline solution must demonstrate not only technical feasibility but also financial viability and a valid customer need [8], [23].

Third, this analysis shows that the variation in the north-south satellite elevation angle (as seen from the consumer ground station) will be accommodated by the consumer ground station. Prior work, as mentioned above, focuses on the ground track rather than the apparent elevation angle variation of the satellite as seen from the consumer ground station. This is significant since it directly impacts the consumer ground station antenna requirements.

Finally, this work shows the connection between the link budget and the consumer ground station and that technology (such as semiconductor solutions) is available that can achieve the main performance metrics such as receive noise figure and transmit output power.

It is important to keep in mind that this work is concerned with systems engineering of a baseline concept. As a result, it is not intended to provide optimization of any particular feature—instead to demonstrate feasibility. Optimization and detailed design will occur in a later design phase of the system. As a result, detailed engineering efforts such as optimization of components and detailed engineering design are out of the scope of this work.

This work is divided into eight sections which demonstrate the soundness of the technical approach supporting the premise that a feasible baseline concept is presented. In Section II, the opportunity motivators are presented. These are the motivations prompting the investigation and are a necessary first step in the engineering of a new system. In Section III, the customer needs analysis is presented. This is an important step since it ensures that the solution will be relevant to particular requirements. Section IV presents details on elliptic orbit design and important orbit characteristics. The main outputs from this section are evidence that a Molniya orbit satellite can provide the necessary coverage and that the variation in elevation is consistent through the orbit to allow single axis consumer ground station antennas and further demonstrates the soundness of systems engineering. Section V describes the consumer ground station. This is where the top level concept for the ground station is presented. The cost of the consumer ground station is considered in Section VI. The cost of the main integrated circuits and antenna circuit boards is analyzed. The link budget is analyzed in Section VII which includes the satellite and ground station up/down links. Finally, the summary is presented in Section VIII along with some suggestions for further study. Together, these sections demonstrate the feasibility of the system and technical soundness of the approach.

II. OPPORTUNITY MOTIVATORS

There are many opportunity motivators for developing HTS solutions. The first one considered here is the need to bridge the disparity gap that exists for access to high speed internet access which is acute for rural areas and marginalized people groups. In the United States of America (USA), for instance, a recent report by the Federal Communications Commission (FCC) found that approximately 39 percent of individuals living in rural areas and 41 percent living in Tribal lands lack access to high speed internet [9]. Their speed benchmark for access is 25Mb/S download and 3 Mb/S upload. The report also concluded that advanced telecommunications capability is not being deployed in a reasonable and timely fashion. These findings are not unique to the USA. For instance, the country of India has a similar disparity between urban and rural for access to wireless [10]. In addition, a recent study as part of the Oxford Internet Institute found a similar result in Britain. The study found that, ‘‘there is a digital divide that separates urban and rural areas in Britain . . . leaving rural areas with a fraction of the service that is enjoyed in urban areas’’ [11]. The report found that poor internet connectivity impacts not only individuals but also small businesses. Satellite internet service is able to reach rural areas which means the lack of rural connectivity provides an opportunity motivator for HTS solutions.

The second opportunity motivator is to meet the connectivity need for internet-of-things (IoT) devices and networks. It is projected that IoT connected end point devices will grow to 25.6 billion units by 2020 [12]. Most of these devices will transfer their data through at least one radio frequency network layer device before being routed to the application layer. From a simplified system level perspective, this arrangement of connectivity is illustrated in Fig. 1. At the sensor level, multiple IoT end points can be aggregated together using gateways that will communicate data back and forth with the network layer. Note from the figure that satellite based connectivity is one of the possible solutions at the

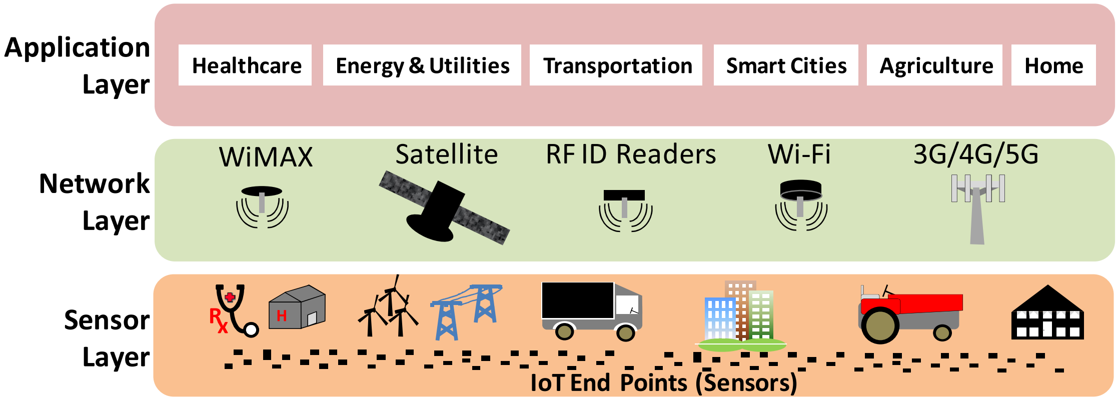


FIGURE 1. IoT system concept showing the sensor layer, network layer which includes satellite systems, and application layer.

network layer. In fact, satellite based IoT type solutions are deployed now for industrial machine to machine (M2M) data communication [13], [14]. In addition, some workers have analyzed the ways to improve IoT device gateways using satellite links and an optimum protocol [15], [16]. In [17] IoT connectivity through gateways has been analyzed with satellites as one of several access methods for networking. This approach is attractive since the gateway device aggregates the information from multiple IoT end points and then packages it for transport to the network layer as illustrated in Fig. 2. A similar approach is taken in [18] where satellites play the same role as Wi-Fi, 4G, and 5G in the network layer. The internet of space (IoS) is proposed in [19] where it is estimated that satellites will play a role in IoT devices for urban, rural, and remote end points. This need for connectivity includes Supervisory Control and Data Acquisition (SCADA) devices which are used in remote monitor and control applications. This need for data connectivity to IoT devices and gateway points provides an opportunity for satellite based solutions.

While consumer internet and IoT connectivity are the main opportunities considered in this article, there are others which provide additional motivation for developing a solution. An example is the delivery of connectivity for corporate enterprise applications such as oil and gas platforms. These systems are often in remote locations and yet require monitoring for security and operational reasons. This is one of the customer groups identified for use of the ViaSat-3 terabit per second satellite planned for launch in 2019 [20]. There are many other industrial connectivity opportunities. Consider, for instance, the connectivity opportunities that the GE Predix platform is projected to create [21]. Another opportunity motivator is commercial airliner in-flight high speed internet. The Bureau of Transportation reported that in 2015 there were nearly 900 million passengers on USA-based flights (both domestic and international) [22]. Existing systems have been deployed to provide services to this market which demonstrate the validity of this opportunity [8]. Depending upon the airline, the in-flight internet access is used by 7-40% of flyers. These in-fight internet services can use satellites for their connectivity. This type of solution will require more complicated terminals in the aircraft. Specifically, it will require antennas that can mechanically or electronically scan in two dimensions to remain connected to the satellite. While this could be a profitable application of the system it is not analyzed in this work.

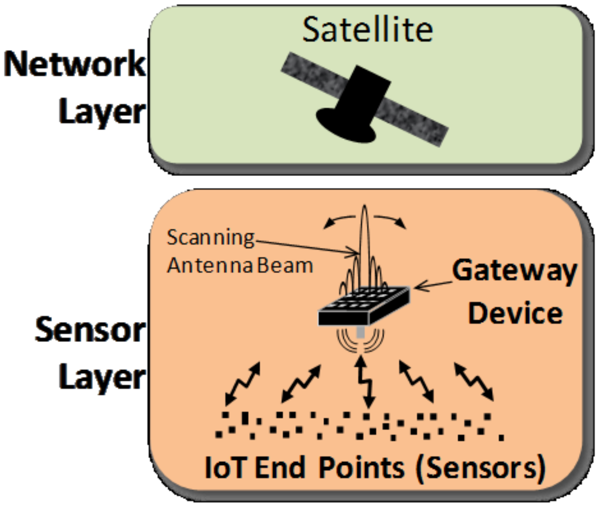


FIGURE 2. A gateway device aggregates the information to/from multiple IoT end points and forwards it to the network layer which may be a satellite.

There are also technical motivations for investigating HTS solutions. In particular, advances in certain technologies now make it possible to develop consumer ground station solutions at price points not previously possible. The point of this article is to show that using elliptical orbit satellites (such as Molniya orbits) combined with recent advancements in integrated circuit (IC) semiconductor technology and reductions in antenna cost (driven by lower cost microwave dielectric materials), it is possible to develop a baseline concept for an affordable HTS solution. The solution will serve as an alternative to geostationary (GEO) and low earth orbital (LEO) satellite systems.

III. NEEDS ANALYSIS

One of the early steps in engineering of a new system is performance of a needs analysis. The goals of the needs analysis are to [23]:

1) Show that a potential market for the new system exists.
2) Show that existing systems have deficiencies that a new system can address or that technology advancements can result in new capabilities that are attractive to customers.
3) Demonstrate that a solution that meets the need(s) is feasible.

This section will examine these three items. The main output from the needs analysis is a set of operational requirements which refer to the capabilities of the system as a whole.

A. POTENTIAL MARKET ANALYSIS

The potential market for the new system is analyzed using a simple income model. While the purpose of this paper is not to present a detailed financial analysis of the potential markets for the baseline concept solution, a simplified market analysis is presented for the two main opportunity motivators from Section I, which are urban internet users and IoT connectivity. Since economic data is available from USA government and industry reports, the potential market analysis is purposely limited to only the USA market. However, this analysis can easily be expanded to other geographic markets.

A summary of the potential market analysis is shown in Table 1. For rural internet usage, the FCC Broad Band Progress report shows that 34 million in the USA are without high speed service [9]. If we assume that each connection will be shared by three individuals, then there are 11 million potential high speed internet users in rural areas. The report also reveals that the adoption rate when broad band is available is approximately 30%. If we assume a broad band service fee of $30 per month, then the annual potential market in the US is $1.19B.

TABLE 1. Total potential market for two opportunities identified.

RURAL INTERNET USAGE		IoT Data Usage	
Potential Users (B)	0.011	End Points Deployed (B)	25.6
Adoption	30%	Adoption	5%
Monthly Fee	$30	Fee/Day/End Point	$0.005
Revenue/Month	$99M	Revenue/Day/End Point	$6.4M
Revenue/Year	$1.19B	Revenue/Year	$2.336B

The table also shows the simplified market analysis for IoT connectivity through satellites. As stated earlier, industry projections are that 25.6B IoT end points will be in service by the year 2020 [12]. If 10% of those units will have data transferred through satellites for a fee of $0.005 per day ($0.15/month), then the revenue per day is $6.4M or $2.336B per year.

There are several potential points of discussion on the market analysis. For instance, the IoT market analysis uses an assumption of $0.005 dollars per day of access. That estimate is a highly discounted and based upon cost for M2M messaging based systems [24]. Costs for M2M connectivity vary from a fixed monthly fee of $13/month to $60/month plus airtime costs of $0.0015 to $0.12 per byte. As further verification of our calculation, the NSR report on M2M and IoT via Satellite projects the total market size to be approximately $2B by the year 2021 [25], [26]. As can be seen in this simplified model, the revenue is linear with fee. This same type of simplification exists in the model for rural internet. In particular, the monthly fee is assumed to be $30. This is a discounted value based on the FCC Broad Band Progress report that "monthly service price offerings as low as $50" [9]. If this monthly fee is used instead, then the annual revenue estimate is $1.98B instead of $1.19B as shown in the table. Therefore, the value in the table can be considered to be a more conservative estimate. Despite the simplifications and conservative income estimates in the financial model, it is useful for serving its purpose which is to show that a viable market exists for the system.

B. REASONS THE NEW SYSTEM IS ATTRACTIVE TO CUSTOMERS

The needs analysis must show that existing solutions have deficiencies that a new system can address or that technology advancements can result in new capabilities that are attractive to customers. This will be achieved by considering the existing solutions and their limitations.

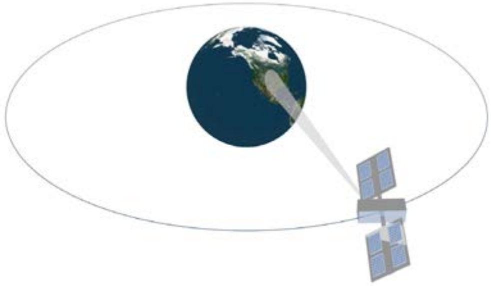


FIGURE 3. Illustration of a geostationary satellite showing that the satellite remains pointed at the same location on earth throughout its orbit.

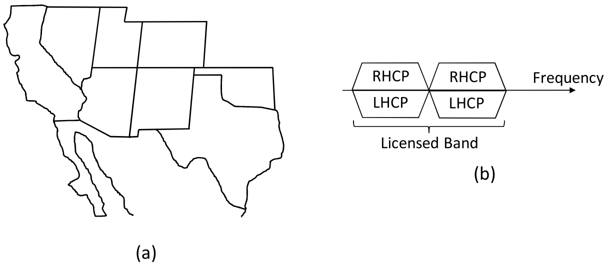
Consider the existing solutions. For instance, Ku-Band and Ka-Band geostationary satellites are being used now for internet delivery. Additional solutions are planned with even greater bandwidth. Consider, for instance, the ViaSat-3 satellite which is planned to provide over 1 Terabit per second of network capacity [27]. A geostationary satellite is illustrated in Fig. 3 which shows the satellite in 'fixed' orbit so it always points to the same location on the face of the earth.

There are existing and planned satellite communications systems that operate at Ku and Ka-Band. Ku-Band is the frequency range from 12-18GHz and is widely used for satellite television services. Ka-Band is the frequency range from 26.5-40GHz and is used for commercial satellite and military applications depending upon the particular frequencies in that range [28]. One benefit of using geostationary satellites for this type of system is the consumer ground station antenna can be aligned once so that it points to the same location in the sky. This is because a geostationary satellite remains pointed at the same position on earth despite the earth's rotation. This is a big benefit since it means that relatively simple and low cost antenna technology can be used for the consumer ground terminal. An example is the now ubiquitous reflector dish and low noise block (LNB) mounted on homes and apartment balconies. Fig. 4 should be a familiar sight to most everyone since it shows a satellite TV dish.

FIGURE 4. **An image that should be familiar to most people since it is of a satellite TV dish pointed to a geosynchronous satellite.**

Research for increasing the data bandwidth of geosynchronous or geostationary satellite systems has focused in three main areas [29]–[31]. First is high spectral efficient waveforms. For instance, in [32] M-ary modulation for M=16, 32, and 64 are compared in the presence of channel non-linearity due to high power amplifier performance for terabit/second satellite systems. M-ary is a modulation scheme commonly proposed for communication satellites which uses multiple simultaneous bits often with quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM) [33]–[35].

The second area of research for geostationary HTS satellites is frequency re-use which means multiple smaller antenna beams are arranged to provide the required coverage. Fig. 5(a) shows a portion of North America (South West USA and Northern Mexico) and a simplified coverage layout with multiple antenna beams of various beam widths. The baseline concept is to use a digital beam forming antenna on the satellite to allow for dynamic beam steering and beam shape control. In the figure, the antenna beams operate in one of two bands and either right hand circular polarization (RHCP) or left hand circular polarization (LHCP) as shown in Fig. 5(b). This arrangement is proposed in [36] to increase frequency re-use. It is also proposed in [32] and [37] except that the multiple-beam user links operate at Ka-Band and gateways operate at other bands such as Q/V band. This approach is attractive because of the wide frequency bands but suffers from attenuation and system cost related to the higher operating frequencies (high frequency components and systems are more costly for the satellite and ground terminal). Another proposed solution in [38] relies on large ground station antennas in dry climates and terahertz operating frequency (300-1086GHz) to achieve greater than one terabit per second of data transfer between ground stations and a geosynchronous (or possibly LEO) satellite. A drawback of this approach is the restriction of the ground terminals to dry climates. The proposed solution investigated in this work operates in Ku-Band and with frequency reuse, but can be applied to other operating bands as well.



(a)

(b)

FIGURE 5. **Example of frequency re-use where (a) multiple antenna beams provide coverage of a portion of North America using (b) frequency and polarization diversity.**

The third area of research for HTS satellites is in the satellite orbit type. As already mentioned, many proposed HTS systems and existing communication satellites use geostationary satellites (at altitudes of 35,786 km). An alternative is medium earth orbit (MEO) satellite systems (orbit altitudes between 2,000 to 35,000 km). An example of MEO satellites is the global positioning system (GPS) with an altitude of 20,200 km. Another alternative is a low earth orbit (LEO) satellite system (orbit altitudes between 160 to 2,000 km). Globalstar satellites are at an altitude of 1,414km and are an example of a LEO system. An important benefit of LEO and MEO satellites is the shorter latency due to the transmission path up to and down from the satellite [39]. The orbit type is part of the alternatives to be considered for HTS satellites.

One of the challenges with MEO and LEO satellites is the complexity of the antenna on the satellite and, more importantly, the consumer ground station. The challenge is achieving a low cost ground terminal since it must track the LEO satellites as they crisscross the sky as described in [40]. This is a challenge since the tracking must be in two dimensions which can be cost prohibitive as discussed in [41]. In particular, scanned arrays are needed which can be either mechanically or electronically scanned [42]. Because of the reliability issues with mechanical scanning, electronic scanning of the antenna beam must be used. In [43] algorithms for tracking LEO satellites using adaptive antennas are considered. However, in that investigation, simple cross-dipole antennas are used which do not meet the system level link budget requirements for high data rates and consumer grade connectivity needs. An alternative is to use two dimensional electronically scanned antenna arrays.

One difficulty with two dimensional electronically scanned consumer ground antennas for tracking LEO satellites is the complexity of the phase shifting elements required to achieve

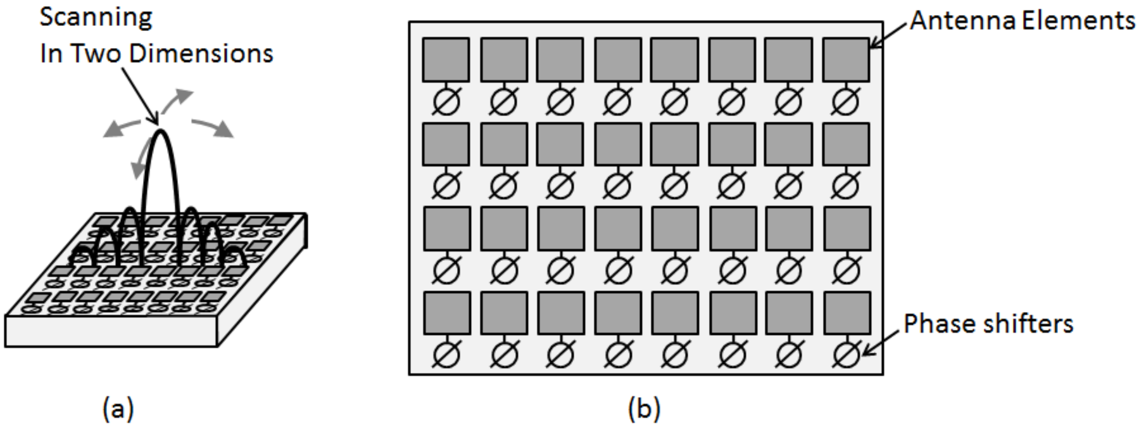


FIGURE 6. Simplified illustration of (a) two dimensional beam steering array with (b) phase shifters at each antenna element to enable the beam steering.

electronic scanning. This is illustrated in Fig. 6 which shows phase shifters located at each antenna element in the phased array. This means the number of phase shifter ICs required for the ground station for a LEO system is proportional to the number of antenna elements. For an antenna with 20 × 20 antenna elements, the number of required phase shifters is 400. This can be reduced if each phase shifter feeds multiple antenna elements. For instance, in a 20 × 20 element array, if each phase shifter feeds 4 elements, then the number of phase shifters is reduced to 100. If each phase shifter cost $5 (US), then the cost of the phase shifters alone can be as high as $500. This means the cost to the consumer would be $1000-$1500 for each antenna and this only accounts for the cost of the phase shifters. When the rest of the ground terminal costs are taken into account, the price tag to the consumer will be much higher. If low cost semiconductor technology such as Si-CMOS devices are used, then the concern is the impact of higher noise figure on the system [44]. While there are some cost reduction methods that can be used as mentioned in [42], it remains unproven if these cost reduction methods will achieve their goals. Next, the needs analysis will consider technology advancements that make a new system attractive to customers.

C. AN ALTERNATIVE SOLUTION WITH ATTRACTIVE FEATURES

While existing geostationary satellites and proposed LEO satellite constellations are viable solutions (with significant unknowns relative to the cost of LEO ground stations), an alternative exists with attractive features. The solution is to use elliptical (in either high apogee or low apogee) orbit satellites constellation with single axis electronic scanning arrays for the consumer ground station. This work focuses on Molniya orbit solutions with high apogee orbits, though low apogee elliptical orbits are an attractive solution and are included here as a viable solution too because of their lower latency and lower path loss. A few of the reasons for the attractiveness of elliptical orbits are:

Feature 1: It overcomes the requirement for 2D scanning that is needed for LEO satellite constellations. This is an important advantage since it means that the consumer ground station will be significantly lower cost. This reason will be explored in more detail below.

Feature 2: There are a limited number of available geostationary slots for new geostationary satellites and alternatives are necessary to support future HTS needs. As mentioned in [45] and [46] the concern is not physical interference between satellites, but rather interference between geostationary satellite signals. The Molniya system avoids this concern since the orbital path is not near geostationary satellite orbits so signal interference is reduced.

TABLE 2. Bandwidth granted By FCC in virtual Geo satellite request [5].

F_{Low} (MHz)	F_{High} (MHz)	Bandwidth (MHz)
3700	4200	500
5925	6725	800
10700	12700	2000
12750	13250	500
13800	14500	700
	Total =	4500

Feature 3: The potential spectrum bandwidth available for elliptical orbit satellites such as Molniya and low apogee elliptical means that they can support HTS service even at Ku-band and lower frequency bands. This means that Ka-band will not be needed and lower cost electronics and antennas can be used on the satellite and on the consumer ground station. This significant is demonstrated by the FCC allowing 4.5GHz of bandwidth to Virtual Geosatellite, LLC [20] in C and Ku-Band as shown in Table 2. The benefit to customers is increase internet speed.

These benefits make elliptic orbit satellite solutions such the Molniya and low apogee elliptic orbits an attractive alternative. We will now describe the Molniya orbit in more detail in the next section.

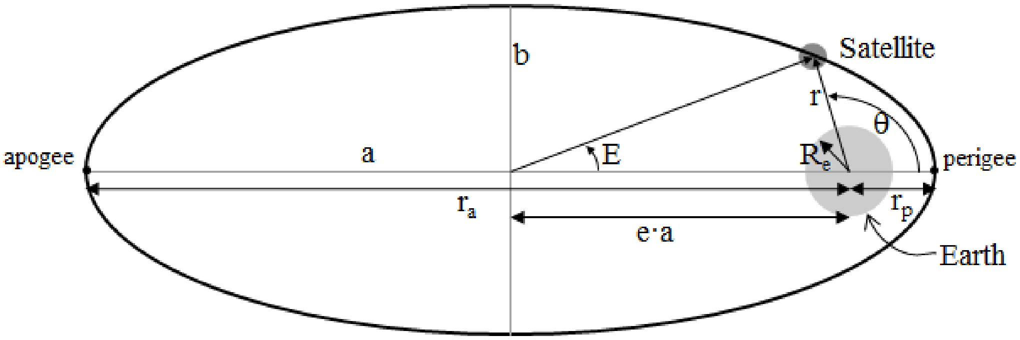


FIGURE 7. Elliptic orbit of a satellite around the earth illustrating the main orbital parameters.

IV. Molniya ORBIT AND GROUND STATION POINTING REQUIREMENT

Elliptic orbit satellites follow an elliptic orbit path around the earth. A Molniya orbit is a type of elliptic orbit and is named after a series of Russian communication satellites that were launched starting in 1965. Those satellites used a highly elliptic orbit which is shown in Fig. 7. Note from the figure the major parameters used to describe a satellite in an elliptic orbit around the earth. The definitions are:

apogee = the point at which the orbit distance is largest.
perigee = the point at which the orbit distance is smallest.
a = semi-major axis = distance from perigee to apogee.
b = semi-minor axis
e = eccentricity
r = distance from the center of Earth and the satellite
θ = angle between the lines from Earth center to perigee and Earth center to the satellite
r_a = distance from Earth center to apogee
r_p = distance from Earth center to perigee
E = angle between the lines from the center of the ellipse to perigee and to the satellite
R_e = radius of Earth

Molniya orbits can be configured with one or multiple satellites. For instance, the orbits for one, three and five satellites are shown in Fig. 8(a), 8(b), and 8(c), respectfully. Note the height of the orbit at apogee compared to perigee. A key feature of Molniya satellites is that each orbit is 12 hours so that the satellite completes two complete orbits per 24 rotation of the earth. This can be seen from the ground tracks for the case of 5 satellites is shown in Figure 8(d). It is important to notice from the figure that the ground paths of the satellites follow a nearly north-to-south path in the center of North America during apogee in the first 12 hours and in the center of Asia (India, Russia, and part of China) during apogee in the second 12 hour period. Because of the high eccentricity, and Kepler's second law which teaches us that the satellite sweeps out equal areas during equal intervals, the time spent at or near apogee is approximately 8 hours of the 12 hour orbit.

Since each satellite follows a nearly straight path (in longitude), Earth locations to the east and west of it will have access to the satellite. This can be seen in Fig. 9(a) which plots the access that a point in Boston, MA, USA will have as a function of time. Note that the satellite constellation provides continual access over the 24 hour period. An important feature, as mentioned earlier, is the elevation angle from the ground location to the satellite will appear to be nearly constant as a function time while the satellite is near apogee. In other words, a user on the eastern side of the ground track will view the satellites as passing at a nearly constant elevation when the user is looking westward. A user on the western side of the ground track will view the satellites as passing at a nearly constant elevation when the user is looking eastward. This is illustrated in Figure 9(b) which shows that the elevation angle varies from approximately 62.7 to 64.2 degrees for a total variation of approximately $+/-0.75$ degrees. This is an important result since this provides the specification for the antenna beam width and pointing accuracy requirement. This means that the antenna can be set to a fixed elevation and as long as the antenna beam width is properly designed so that the satellite remains in the consumer ground station antenna beam width as it varies slightly in elevation. This arrangement will ensure the constellation of satellites will be continually in the consumer ground antenna beam width. The simulations were performed with the following orbital parameters for the Satellite:

Semimajor Axis: 26,553.4 km
Eccentricity: 0.56
Inclination: 47 degrees
Argument of Perigee: 270 degrees
RAAN: 153 degree (for Satellite 1)
True Anomaly: 0 degrees

At this inclination, the Argument of Perigee will be perturbed over time. This will require fuel burn to keep the satellite at the correct Argument of Perigee. Other inclinations such as a critical inclination of 63.4 degrees can also be used which will overcome the perturbation of the Argument of Perigee.

V. CONSUMER GROUND STATION

One benefit of the tight variation in elevation is that a simple ground station can be used. This is because the

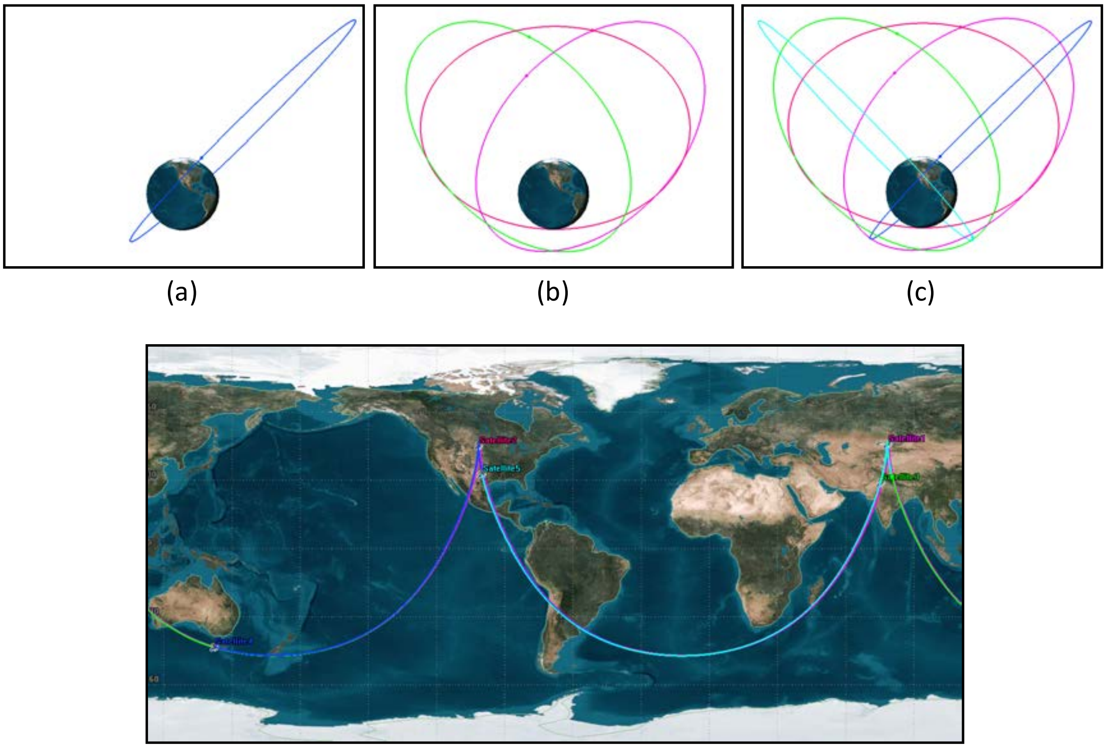


FIGURE 8. **The Molniya orbits for (a) one, three, and five satellites, and (b) the ground tracks for the case of five satellites (images generated using System Tool Kit (STK) software from Analytical Graphics, Inc.).**

ground station will scan electronically in only one direction since the elevation setting will be fixed during installation. Fig. 10(a) is a simplified illustration showing the concept of an array antenna. Fig 10(b) shows one dimensional line array elements each with a single phase shifter attached. The line arrays are combined to create the 2 dimensional array. This is a significant improvement over what is required for LEO satellites since the number of required phase shifters in the consumer ground station is reduced. For instance, for an array with 20 × 20 elements, only 20 phase shifters are required which is much lower cost than the 100 to 400 required for the ground station in a LEO system as previously discussed in Section II.

Part of the reason fewer phase shifters is a benefit is they are high performance and costly semiconductor components. As part of the systems engineering evaluation, a trade study was conducted to determine the candidate semiconductor for the phase shifter. The candidate technologies are silicon complementary metal-oxide-semiconductor (Si-CMOS), silicon germanium (SiGe), gallium arsenide (GaAs), and indium phosphide (InP). The trade study analyzed seven criteria for selecting the semiconductor material. The selection criteria along with a description are:

A. INTEGRATION COMPLEXITY

The phase shifter requires a high level of circuit complexity. This is because it contains many different types of circuits such as low noise amplifiers, high power amplifiers, operational amplifiers, digital control circuits, analog to digital converters, and temperature compensation circuits. The functionality of these circuits contribute to the overall function and performance of the system. As a result, this criteria is important since it has a direct impact on the customer need for high availability and data rate on both up and down link.

B. RELATIVE COST

The active circuits that form the integrated circuit are fabricated onto semiconductor wafers. There are two important factors impacting the relative cost of semiconductor wafers. The first is the raw material cost. The second is the volume of wafers produced per year which is normally reported in units of million square inches (MSI). As more wafers are produced, the cost of each wafer will be lower. Therefore, semiconductors with lower raw material cost and high production volume will result in lower cost integrated circuits. This has an important impact on the customer need for a low cost solution.

C. PRODUCTION CAPACITY

This is the capacity of semiconductor foundries to fabricate the integrated circuits onto the raw wafers. This is an important selection criteria since the volume of finished wafers required to meet the demand for consumer ground stations must not be a significant percentage of the world wide capacity. Otherwise, the cost of the foundry processing

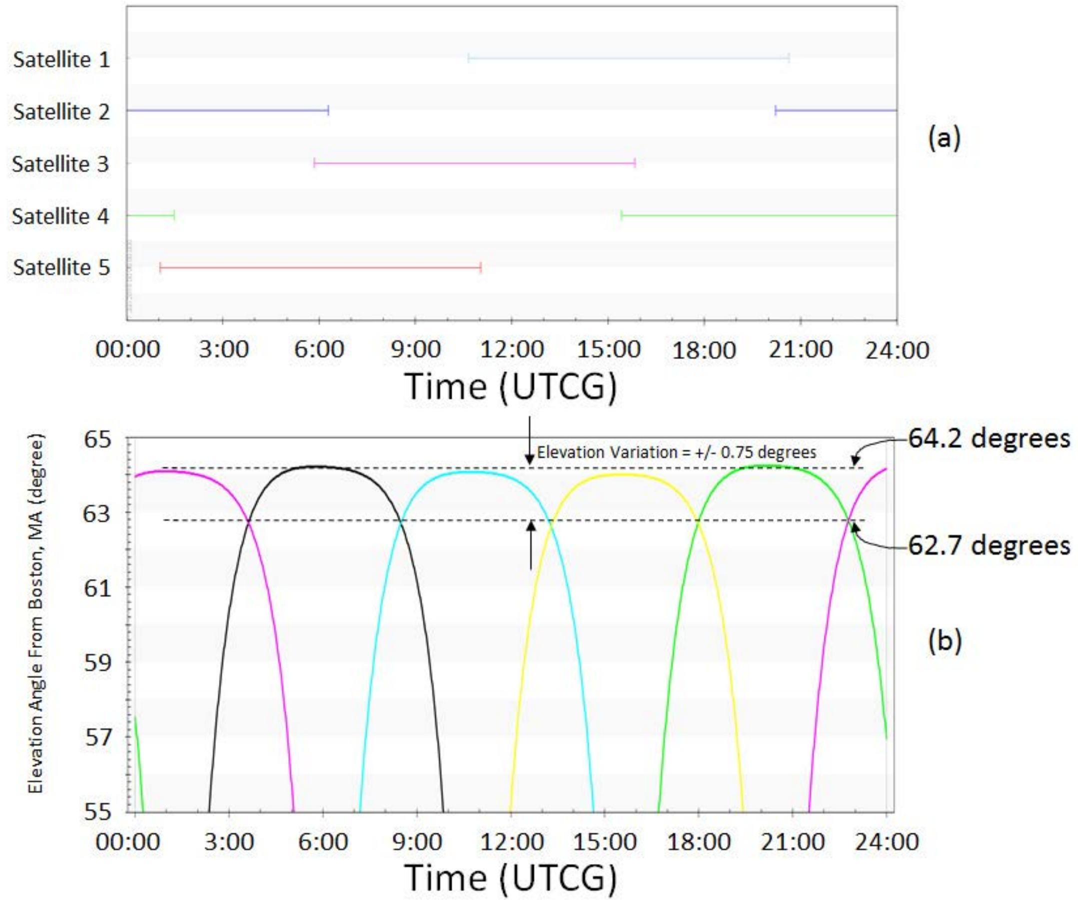
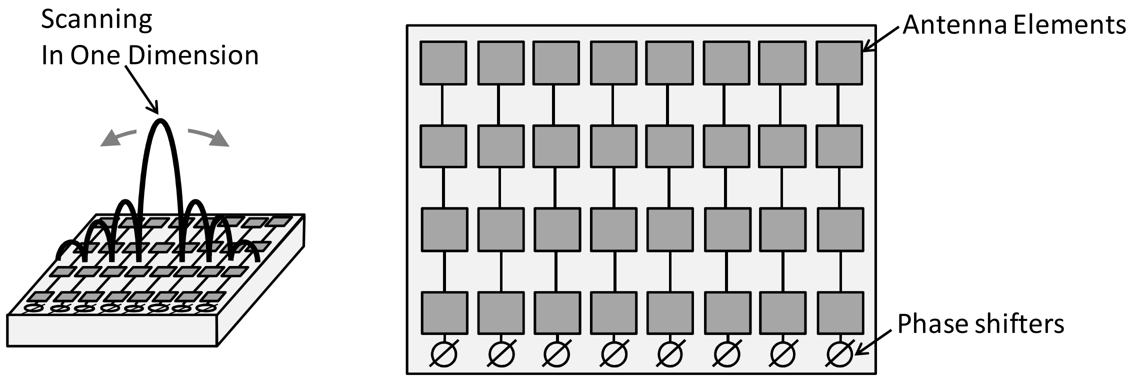


FIGURE 9. The 5 satellite constellation provides (a) complete coverage as seen from Boston, MA, and (b) a variation of approximately $+/-0.75$ degrees in elevation. (graphs generated using System Tool Kit (STK) software from Analytical Graphics, Inc.).



(a) (b)

FIGURE 10. Illustration of the (a) one-dimensional scanning array with (b) phase shifters at each column of antenna elements to enable the beam single dimension beam steering.

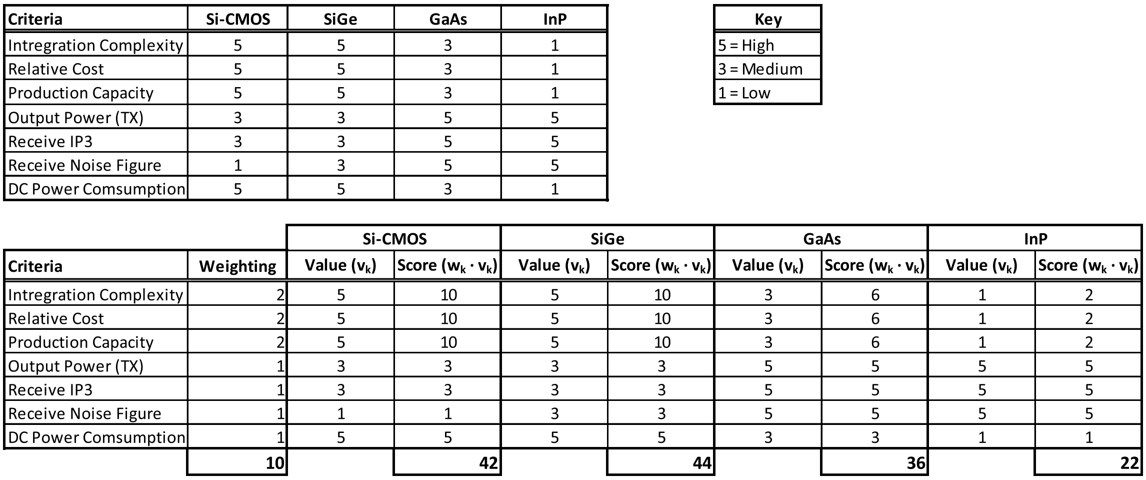
will increase and the ability to meet demand will be impacted. This has an important impact on the customer need for a low cost solution.

D. OUTPUT POWER (TX)

The transmit (TX) output power of the semiconductor material directly impacts the effective isotropic radiated power (EIRP) of the consumer base station. This, in turn, is a major determining factor for the up-link (ground to satellite) link budget. This translates into an impact on the customer need for uplink data connection speed.

E. RECEIVE IP3

The receiver third order intercept (IP3) must be high enough that it will achieve the required dynamic range. IP3 determines the high side of the dynamic range of the receiver.



Criteria	Si-CMOS	SiGe	GaAs	InP
Intregration Complexity	5	5	3	1
Relative Cost	5	5	3	1
Production Capacity	5	5	3	1
Output Power (TX)	3	3	5	5
Receive IP3	3	3	5	5
Receive Noise Figure	1	3	5	5
DC Power Comsumption	5	5	3	1

Key
5 = High
3 = Medium
1 = Low

		Si-CMOS		SiGe		GaAs		InP	
Criteria	Weighting	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)
Intregration Complexity	2	5	10	5	10	3	6	1	2
Relative Cost	2	5	10	5	10	3	6	1	2
Production Capacity	2	5	10	5	10	3	6	1	2
Output Power (TX)	1	3	3	3	3	5	5	5	5
Receive IP3	1	3	3	3	3	5	5	5	5
Receive Noise Figure	1	1	1	3	3	5	5	5	5
DC Power Comsumption	1	5	5	5	5	3	3	1	1
	10		42		44		36		22

FIGURE 11. Trade study result shows that Si based semiconductors are preferred to GaAs and InP solutions.

In other words, it sets the maximum signal level that can enter the receiver without the signal being distorted. This includes not only the desired signal from the satellite, but also any other undesired signals that are at or near the same operating frequency of the receiver. This is important for cases of possible interfering signals which may overwhelm the receiver. This translates into an impact on the customer need for a high level of availability of the system.

F. RECEIVE NOISE FIGURE

The receive noise figure, like IP3, impacts the minimum signal the receiver in the consumer ground station can distinguish. It sets the noise floor and the lower end of the dynamic range. The receiver noise figure determines the G/T of the consumer ground station which will be discussed in Section V. This translates into an impact on the customer need for a high level of availability of the system and on the maximum data rate of the system.

1) DC POWER CONSUMPTION

This is a factor for thermal reasons. Integrated circuits which consume more electric power also generate more heat. The heat degrades the performance and lifetime of the integrated circuits. Therefore, lower DC power consumption translates, in general, to more reliable electronics. This impacts the customer need for a reliable system. Given these seven selection criteria, a trade study was conducted to determine the semiconductor material that should be selected for the phase shifters used in the consumer ground station. The trade study spreadsheet is shown in Fig. 11. Note that the there is a clear distinction between the silicon based materials (Si-CMOS and SiGe) and GaAs and InP with Si based solutions being preferred.

Each of the criteria is given a weighting, Wk, which is related to its importance to the mission of the system. Each of the energy generation options is assigned a value, Vk, for its ability to achieve each of the criteria. If this is done, then the score for each option is given by:

$$Score = \sum_{k=1}^{n} W_k V_k \tag{1}$$

Where n = the number of criteria, which is seven in our case. The trade study was implemented in a spread sheet.

The justification for the assigned values for a few of the criteria will now be discussed. For integration complexity in Si-CMOS and SiGe semiconductor processes, it is easier to include functions such as operational amplifiers, digital control circuits, analog to digital converters, and temperature compensation circuits as compared to GaAs and InP. This is mainly due to factors such as the available transistor types and number of metal layers available in the foundry processes. For these reasons, Si-CMOS and SiGe scored higher than GaAs and InP.

The relative cost of the raw material and cost of the semiconductor wafers varies. The active circuits that form the integrated circuit are fabricated onto semiconductor wafers. The cost of Silicon is low compared to GaAs and InP due in large to the fact that it is the second highest concentration element (at 27.7%) on the earth's crust. Also, the volume of silicon wafers produced is much higher than for GaAs or InP. For instance, the volume of Si wavers produced in 2016 will be nearly 11,000 million square inches (MSI) compared to approximately 150 MSI for GaAs [47], [48]. For these reasons, Si-CMOS and SiGe scored a higher value than GaAs and InP.

Despite the performance limitations of Si-CMOS and SiGe compared to GaAs and InP, they are the better choice as the semiconductor material. The relative weighting score between them is very close with SiGe having a slightly higher score due to better noise figure performance. An advanced development effort should be conducted so that major subsystems simulated and/or fabricated with Si-CMOS and SiGe can be compared to make a final choice between the semiconductor material.

The criteria of output power, IP3, and noise figure are better for GaA and InP since they are wider band gap materials and have better electron transport compared to Si-CMOS and SiGe. Work on comparing Si-CMOS and SiGe demonstrates that SiGe has the performance edge over Si-CMOS for noise figure, IP3, and output power [49], [50]. As a result, SiGe scores better than Si-CMOS but lower than GaAs and InP on these performance criteria.

Also, in [51] key performance parameters such as noise figure, gain, 1 dB compression point, and IP3 for low noise amplifiers are compared for SiGe and GaAs. An important finding is that SiGe is able to achieve approximately 1.4dB of noise figure at 12GHz. The output power of SiGe for the uplink will stretch its performance limits. However, output power levels of SiGe at Ku-band have been demonstrated at 24.45dBm [52] and 850mW was demonstrated at 10.5GHz [53]. Similar performance levels for SiGe will be used in the system level link budget analysis which will show the feasibility of its usefulness for consumer ground stations.

The design of antenna for the ground station must account for multiple, often competing, requirements. Three of the requirements that will be addressed here are:

1. It must be capable of providing the required gain to close the link with the satellite.
2. Have a wide enough beam width that the satellite will remain within the main beam through the required portion of the orbit.
3. Scan electronically without introducing grading lobes.

To determine the ability of the ground station antenna to achieve these requirements, we must first consider the antenna as an array of radiating elements. This is depicted in Fig. 12. Note that there are M columns of line arrays each with N elements for a total of MxN elements. Thus, for an array for M = 20 and N = 20, there will be 400 elements. Also notice that there are M elements spaced apart in the x-direction by d_X and N elements spaced apart in the y-direction by d_Y.

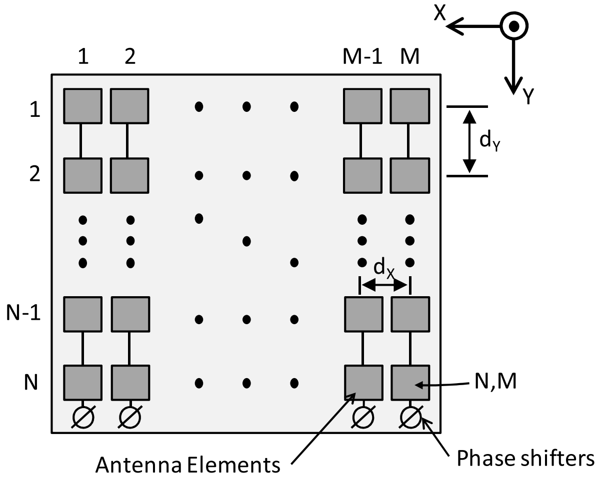


FIGURE 12. Ground station antenna represented as an array of antenna elements with M columns and N rows.

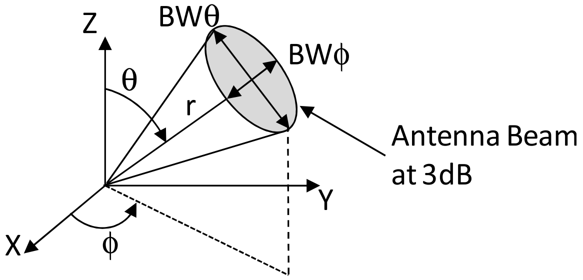


FIGURE 13. Antenna beam width in the far field.

Given the configuration in the figure, the antenna will create a beam in the far field with a beam width as defined in Fig. 13. In the direction broadside to the antenna, the antenna 3dB beam width in degrees can be approximated using

$$BW_\theta = 50.76^\circ \frac{\lambda}{N d_Y} \tag{2}$$

and

$$BW_\phi = 50.76^\circ \frac{\lambda}{M d_X}. \tag{3}$$

Where, λ = the wavelength at the operating frequency. Using (2) and (3), the magnitude of the directivity can be approximate by

$$D(\theta, \phi) = \frac{16}{\sin(BW_\theta)\sin(BW_\phi)}. \tag{4}$$

If the efficiency of the antenna is given by ε_{eff}, then the gain of the antenna in dB can be calculated using

$$G(dB) = 10\log_{10}(\varepsilon_{eff} D). \tag{5}$$

Assuming the center of the band to be 11.7GHz, antenna efficiency of 65%, the number of elements in array are N = 20, M = 20, element spacing of d_X = 15.38mm (0.6λ), d_Y = 23.07mm (0.9λ), the calculated antenna parameters are

$$BW_\theta = 2.8^\circ, \quad BW_\phi = 4.23^\circ, \; Gain = 34.57dB.$$

Note that the element spacing is much wider in the y-direction since the antenna will not be scanning along that axis, but the element spacing is just above a half-wavelength in the x-direction since that is the direction the antenna will be scanning. This arrangement minimizes the presence of grading lobes as the antenna is scanned. Since the beam width in the non-scanned direction is 2.8°, this will ensure that the satellites remain in the antenna's main beam as they vary by +/−0.75° in their north-south ground track as discussed above.

This level of investigation into the antenna design demonstrates the feasibility. It is suggested that an advanced design effort is in order to further demonstrate either through detailed simulations or, preferably, through testing that the antenna design concept will achieve the gain, beam width, and grading lobe free scanning that is required.

VI. COST OF THE GROUND STATION

The cost of the ground station can be analyzed by considering the two main contributors to the cost. The first is the cost of the antenna circuit board. It is a printed circuit board (PCB) but cannot be fabricated using standard PCB material such as FR-4. Rather, it must be fabricated using high quality laminates with low losses at the frequency range of the satellite signals. This is critical to the proper operation of the antenna otherwise a large portion of the signal will be absorbed by the PCB material rendering the system unusable. Until recently, the cost of the high quality laminates has been prohibitive since they use Polytetrafluoroethylene (PTFE) materials which have been relatively high cost in the past. However, the cost of PTFE based low loss microwave laminates are \$58 to \$80 per square meter in high volume [54]. This means that a 0.6 m^2 antenna will have approximately \$35 of antenna PCB board cost. As production volumes increase, there will likely be additional cost savings.

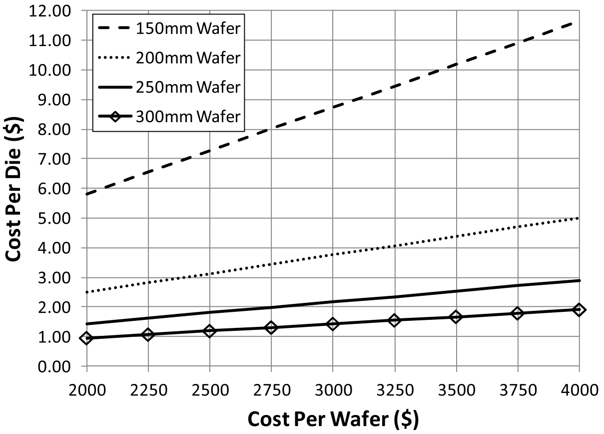


FIGURE 14. **The cost per phase shifter integrated circuit as a function of wafer cost and wafer size (assumes a die size of 5 × 5mm, 80% yield, and unpackaged die).**

The other main cost contributor to the ground station is the cost of the integrated circuit phase shifters and amplifiers. Since the trade study in the last section showed SiGe as the preferred semiconductor material, the cost analysis will based on it. Fig. 14 shows the cost per die for the phase sifter integrated circuit with the associated control electronics and amplifiers. At a wafer cost of \$2500 on a 200mm SiGe fabrication line, the cost of each integrated circuit is approximately \$3.13 each, and on a 250mm wafer, the cost is approximately \$1.81 before packaging. For an array of 20 line arrays, the total die cost will be approximately \$36 to \$63. As the semiconductor industry moves to 300mm wafers, the cost of the die will drop to approximately \$1.19 each for a total die cost per array of \$26.

This analysis shows that the main cost drivers for the consumer base station, the antenna PCB and integrated circuit phase shifters, can be fabricated for a cost that is approximately \$61 (\$35 for the antenna and \$26 for the integrated circuits).

VII. LINK BUDGET

The purpose of this section is to show through modeling that it is possible to achieve uplink and downlink with acceptable margin using subsystems and components that are low risk. Low risk means that the required hardware components have been previously demonstrated in a relevant environment which is Technology Readiness Level (TRL) 5 or 6 [55]. The key functional elements that affect the link are the:

1) Effective Isotropic Radiated Power (EIRP) of the transmitter
2) Losses (free-space and atmospheric)
3) Channel bandwidth
4) Receiver G/T

These four elements will be investigated and viable hardware solutions with low risk will be described. Prior to that, however, the block diagram of the satellite link must be described.

The block diagram of a link between a satellite and ground station is shown in Fig. 15. The downlink (satellite to ground terminal) is shown in Fig. 15(a) and the uplink (ground station to satellite) is shown in Fig. 15(b). For the downlink, the satellite operates as the transmitter (TX) with a high power amplifier and transmit antenna and the ground terminal operates as the receiver (RX) with a receive antenna and low noise amplifier. For the uplink, the arrangement is just the opposite with the ground terminal functioning as the TX with high power amplifier and transmit antenna and the satellite functioning as the RX with a receive antenna and low noise amplifier. It is also important to note that in the receive cases there is an added noise which is the system noise temperature. It accounts for all the system noise contributions such as from the low noise amplifier and antenna. The definitions for the elements in the block diagram are:

G_{TS} = Satellite transmit antenna gain (downlink)
P_{TS} = Satellite power amplifier out power (downlink)
G_{RS} = Satellite receive antenna gain (uplink)
P_{RS} = Satellite signal power received (uplink)
T_{SYS-S} = Satellite receiver system noise power (uplink)
G_{RG} = Ground station receive antenna gain (downlink)
P_{RG} = Ground station signal power received (downlink)
T_{SYS-G} = Ground station receiver system noise power (downlink)
G_{TG} = Ground station transmit antenna gain (uplink)
P_{TG} = Ground station power amplifier out power (uplink)
d = distance between the satellite and ground terminal antenna

Between the satellite and the ground terminal free-space, L_o, and atmospheric losses, L_a, occur. Free-space losses are also called spreading losses and are defined by the IEEE Std 145-2013 as “the loss between two isotropic radiators in free space, expressed as a power ratio [56].” The atmospheric loss is due to attenuation from effects such as rain fade. The free-space loss is proportional to the square of the distance between the satellite and ground terminal and is given by [57]

$$L_o = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{6}$$

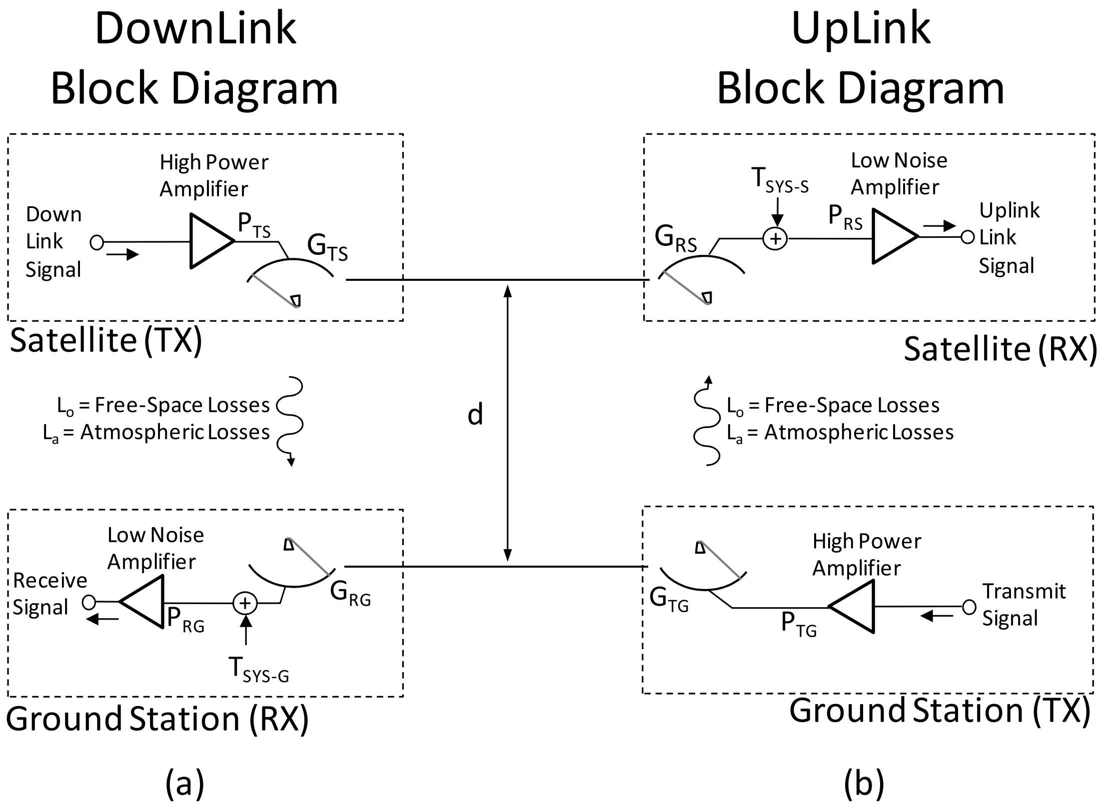


FIGURE 15. Simplified block diagram of the satellite (a) downlink with the satellite as the transmitter (TX) and ground terminal as receiver (RX), and (b) uplink with the ground terminal as the TX and satellite as RX.

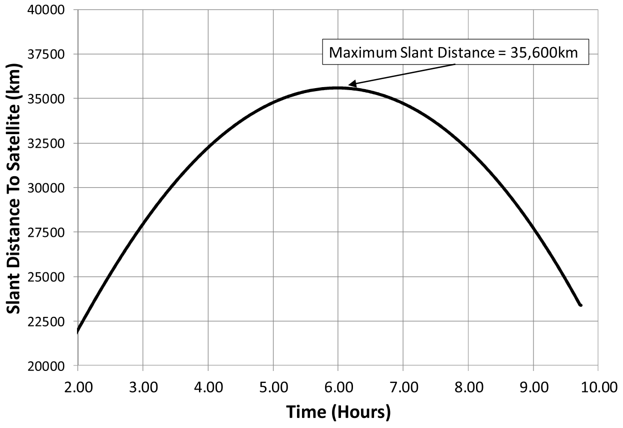


FIGURE 16. Slant distance from Boston, MA to satellite shows the maximum at 35, 600km (simulations performed using System Tool Kit (STK) software from Analytical Graphics, Inc).

Where:

$$\lambda = \text{wavelength of the signal}$$

The system noise temperature is has two components which are the noise temperature of the antenna, T_A, and the noise temperature of the receiver, T_{RX} which can be written as

$$T_{SYS} = T_A + T_{RX} \tag{7}$$

The noise temperature of the antenna is affected by where the antenna beam is pointed. If the antenna has low side lobes and is on the earth pointed up to cold clear sky then the noise temperature will be low. If the antenna is mounted on a satellite and is pointed toward the warm earth, then the noise temperature will be much higher. The noise figure (NF) of the receiver is normally specified and includes the feed loss, L_F, plus the noise figure of the electronics, NF_{LNA} which can be written as

$$NF(dB) = NF_{LNA}(dB) + L_F(dB) \tag{8}$$

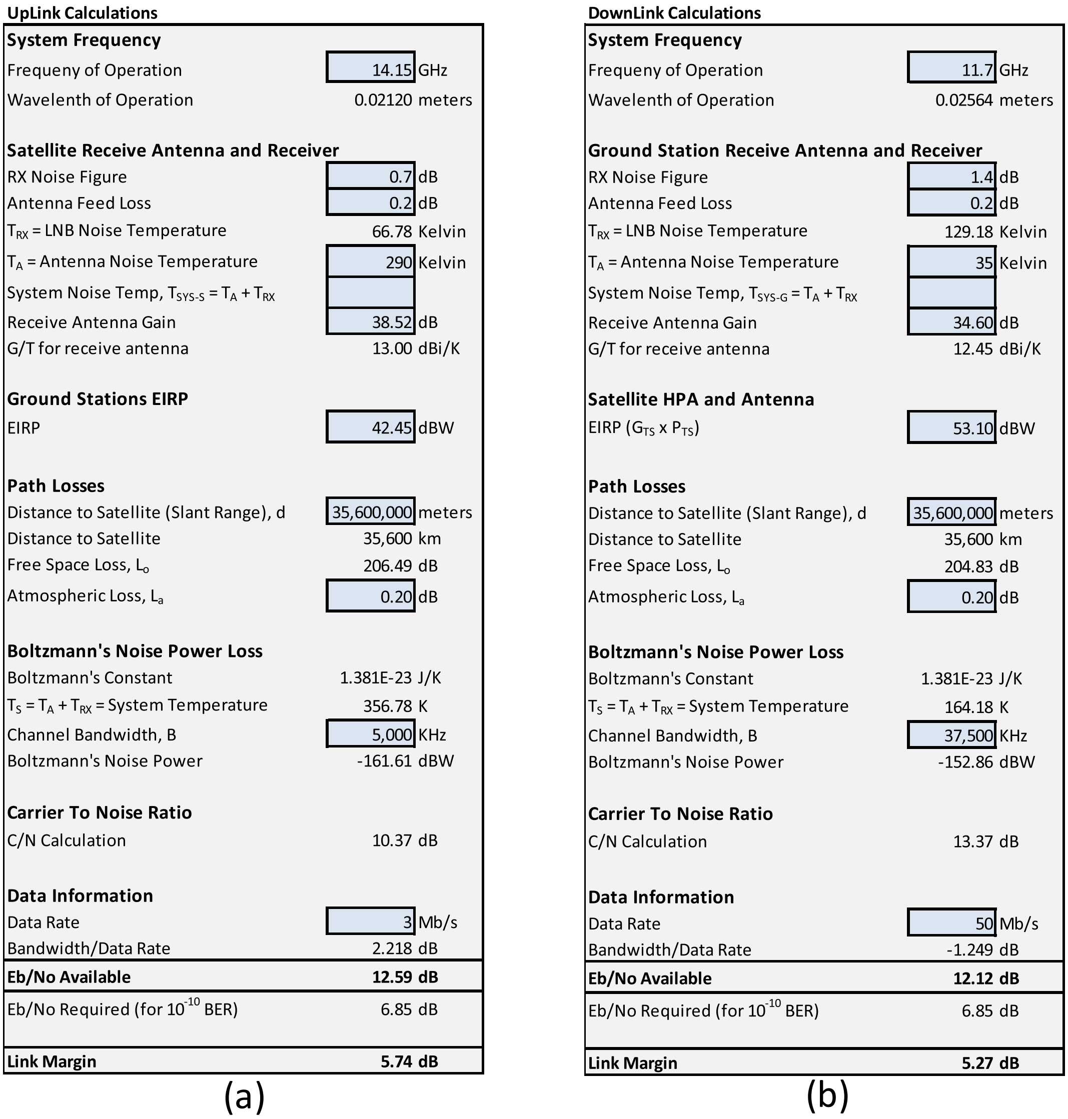
but the receiver noise temperature can be calculated from NF using

$$T_{RX} = T_{REF}\left(10^{NF(dB)/10} - 1\right) \tag{9}$$

The system designer needs to know the signal to noise ratio (S/N) of the system being designed. This is because it provides a measure of quality (or capacity) of the communication channel based upon Shannon's channel capacity theorem

$$C = B \cdot Log_2(1 + S/N) \tag{10}$$

which gives the channel capacity in bits per second for a given system signal to noise ratio and channel bandwidth B. The signal to noise ratio for the uplink (consumer ground station



UpLink Calculations		
System Frequency		
Frequeny of Operation	14.15	GHz
Wavelenth of Operation	0.02120	meters
Satellite Receive Antenna and Receiver		
RX Noise Figure	0.7	dB
Antenna Feed Loss	0.2	dB
T_{RX} = LNB Noise Temperature	66.78	Kelvin
T_A = Antenna Noise Temperature	290	Kelvin
System Noise Temp, $T_{SYS-S} = T_A + T_{RX}$		
Receive Antenna Gain	38.52	dB
G/T for receive antenna	13.00	dBi/K
Ground Stations EIRP		
EIRP	42.45	dBW
Path Losses		
Distance to Satellite (Slant Range), d	35,600,000	meters
Distance to Satellite	35,600	km
Free Space Loss, L_o	206.49	dB
Atmospheric Loss, L_a	0.20	dB
Boltzmann's Noise Power Loss		
Boltzmann's Constant	1.381E-23	J/K
$T_S = T_A + T_{RX}$ = System Temperature	356.78	K
Channel Bandwidth, B	5,000	KHz
Boltzmann's Noise Power	-161.61	dBW
Carrier To Noise Ratio		
C/N Calculation	10.37	dB
Data Information		
Data Rate	3	Mb/s
Bandwidth/Data Rate	2.218	dB
Eb/No Available	**12.59**	**dB**
Eb/No Required (for 10^{-10} BER)	6.85	dB
Link Margin	**5.74**	**dB**

(a)

DownLink Calculations		
System Frequency		
Frequeny of Operation	11.7	GHz
Wavelenth of Operation	0.02564	meters
Ground Station Receive Antenna and Receiver		
RX Noise Figure	1.4	dB
Antenna Feed Loss	0.2	dB
T_{RX} = LNB Noise Temperature	129.18	Kelvin
T_A = Antenna Noise Temperature	35	Kelvin
System Noise Temp, $T_{SYS-G} = T_A + T_{RX}$		
Receive Antenna Gain	34.60	dB
G/T for receive antenna	12.45	dBi/K
Satellite HPA and Antenna		
EIRP (G_{TS} x P_{TS})	53.10	dBW
Path Losses		
Distance to Satellite (Slant Range), d	35,600,000	meters
Distance to Satellite	35,600	km
Free Space Loss, L_o	204.83	dB
Atmospheric Loss, L_a	0.20	dB
Boltzmann's Noise Power Loss		
Boltzmann's Constant	1.381E-23	J/K
$T_S = T_A + T_{RX}$ = System Temperature	164.18	K
Channel Bandwidth, B	37,500	KHz
Boltzmann's Noise Power	-152.86	dBW
Carrier To Noise Ratio		
C/N Calculation	13.37	dB
Data Information		
Data Rate	50	Mb/s
Bandwidth/Data Rate	-1.249	dB
Eb/No Available	**12.12**	**dB**
Eb/No Required (for 10^{-10} BER)	6.85	dB
Link Margin	**5.27**	**dB**

(b)

FIGURE 17. Link budget calculations for (a) the uplink, and (b) the downlink.

to satellite) is calculated using

$$\left.\frac{S}{N}\right|_{Satellite} = P_{TG} G_{TG} \cdot \left(\frac{\lambda}{4\pi d}\right)^2 L_a \frac{1}{kB} \frac{G_{RS}}{T_{SYS-S}} \qquad (11)$$

The first two terms relate to the ground station antenna and output power, the middle terms to the channel and losses, and the final term relates to the satellite receive antenna and system noise temperature. For the downlink (satellite to ground consumer station), the signal to noise ratio is given by

$$\left.\frac{S}{N}\right|_{Ground\ \ Station} = P_{TS} G_{TS} \cdot \left(\frac{\lambda}{4\pi d}\right)^2 L_a \frac{1}{kB} \frac{G_{RG}}{T_{SYS-G}} \qquad (12)$$

It is normal to use the effective isotropic radiated power (EIRP) which is the product of the transmit power and transmit antenna gain. In this case

$$EIRP_S = \text{Satellite EIRP} = P_{TS} G_{TS} \qquad (13)$$

$$EIRP_G = \text{Ground Station EIRP} = P_{TG} G_{TG} \qquad (14)$$

Since satellites use digitally modulated and coded channels, it is more convenient to use energy per bit transmitted normalized to the power spectral density of the noise, or E_b/N_o. It is related to signal to noise ratio by

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B}{R} \qquad (15)$$

Where S/N is calculated from (11) or (12) depending upon whether the uplink or downlink are being analyzed, B is the channel bandwidth and R is the digital data rate. If satellite TV providers are used as a frame of reference for the required Eb/N0, then the required E_b/N_0 for the downlink (satellite to ground station) will be between 6.5 and 7.2dB without margin which provides a 10^{-10} bit error rate (BER) as described in [58]. For the work, we will use the E_b/N_0 requirement 6.85dB which is between these two values.

Using (11) and (12) requires the knowledge of the slant distance from the consumer ground station to the satellite.

Simulations of the Molniya orbit using the same orbit parameters as for Fig. 8 and Fig. 9. The result is shown in Fig. 16 which shows the maximum slant range as 35,600km.

Referring back to Table 2, the downlink and uplink frequencies must be assigned to particular frequency bands. Since consumer internet access is non-symmetrical, with high download and low upload speeds, it makes sense to allocate the wider Ku-band at 10.7-12.7GHz to the downlink and the narrow Ku-Band from 13.8-14.5GHz to the uplink. One benefit of this arrangement is the separation of 1.1GHz between the up and down links which is helpful for isolation reasons. The rest of the spectrum (1.8GHz) in Table 2 can be allocated to providing access and control to the satellite.

Based upon this frequency plan and (7), and (8), the link analysis was performed. For the uplink, the center of the band was chosen at 14.15GHz and the link calculations spreadsheet results are shown in Fig. 17(a). It shows the calculated Eb/N0 is 12.59dB which provides a link margin of 5.7dB beyond the goal of 6.85 dB. For the downlink, the center of the band was chosen at 11.7GHz and the link calculations spreadsheet results are shown in Fig. 17(b). It shows the calculated Eb/N0 is 12.12dB which gives a link margin of 5.3dB beyond the goal of 6.85dB. This analysis is for a Molniya orbit satellite which has a more challenging link budget than a low apogee elliptic orbit since the Molniya orbit apogee is approximately the same distance as the radius of a GEO satellite. The point of the analysis is that it is possible to close the link with margin for the Molniya orbit.

Based on this link budget there are a several requirements that are placed on the consumer ground terminal and satellite. First, the receive noise figure for the ground station on the downlink must be 1.4dB. As stated in Section III, prior work in [52] demonstrates the ability of SiGe to achieve this noise performance. Second, the ground station uplink transmit EIRP is 42.45 dBW with an antenna gain of 34.6dB. This means that the ground station must have a transmit power of 42.45dBW-34.6dB = 7.85dBW which is 6.1W. If there are twenty line arrays, then this means that each line array must produce 0.305W or 24.8dBm of transmit power. This level of output power from SiGe is within the range of demonstrated performance as discussed in Section III. Third, the satellite antenna gain is 38.52dB which can be achieved with an antenna diameter less than 1 meter. Fourth, the satellite receive noise figure is set to 0.7dB which means that the satellite G/T is required to be 13dB which may be a bit aggressive. However, next generation satellite performance is being extended to achieve the HTS goals so that this requirement should be carefully considered.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this work are that an operational need exists for HTS satellites and a feasible solution exists. These conclusions are supported by analysis in five areas. First, the needs analysis focused on consumer internet users in rural and remote areas and connectivity for IoT end points and access points. A simple financial model showed that these needs provide a financial incentive for development of a solution. Recent technical advances in SiGe integrated circuit technology and cost reductions in circuit board materials for antennas provide additional incentive for the new system.

Second, several alternatives for the system solution were considered including geostationary, low Earth orbital (LEO), and Molniya orbit satellite constellations. The analysis considered the whole system including the consumer ground station. The Molniya orbit solution was chosen because of the available bandwidth at C-Band and Ku-Band which overcomes the spectrum crowding of geosynchronous satellites and because of the lower cost consumer ground station compared to LEO solutions.

Third, the Molniya solution was investigated in detail to ensure that a feasible system level solution exists. Orbital dynamics were considered and it was shown that a constellation of five satellites can provide continuous coverage for the USA and parts of Asia. It was also shown that the elevation, as seen from the ground station, has a variation of only $+/-0.75$ degrees which is within the main beam of the consumer ground station.

The fourth investigation in this work that supports the conclusions is the consumer ground terminal. It was analyzed from a cost and available technology perspective. It was found that the cost of the key integrated circuit, the phase shifter, is affordable now and will become more affordable as industry migrates from 200mm to 250mm and 300mm wafers. Fifth, the link budget was analyzed and it was found that the link can be closed with approximately 5dB of margin for both up and down links. The work in these five areas supports the conclusions that there is an operational need for the new system and that a feasible solution is exists.

Additional work should be performed on this system in at least six different areas. First, the overall system affordability should be investigated in more detail. Specifically, the cost of developing and deploying the constellation versus the financial benefit must be analyzed. Second, a more extensive analysis of Molynia orbit satellite elevation as a function of obit parameters over the desired coverage area should be conducted. In fact, the trade space of orbit parameters should be examined to minimize the elevation variation at all points in the desired coverage area. Third, an advanced development effort was suggested in the analysis to aid in choosing between the use of SiGe or Si-CMOS for the phase shifter. This is important since there are cost advantages for choosing Si-CMOS over SiGe but there are unanswered questions with the ability of Si-CMOS to meet the noise figure and output power levels required. Fourth, an additional advanced development effort is suggested for the antenna for supporting circular polarization. Fifth, there are certain benefits that a low apogee elliptical orbit offers over a Molniya orbit and yet both benefit from wide available bandwidth. Therefore, a further refinement in this analysis is to optimize the type of elliptical orbit with variables such as apogee and inclination being important trade parameters. Sixth, a comparision of the capital cost for developing a global GEO versus elliptic orbit system should be compared. Of course, there are many other areas of work that can and should be conducted to further this system concept toward implementation.

ACKNOWLEDGMENT

The authors would like to thank Richard Petrisevac for his suggestions on the plots in Fig. 9.

REFERENCES

[1] P. Christopher, "Molniya system alternatives for geostationary satellite systems with applications to 72-100GHz systems," in *Proc. Ka Broadband Conf.*, Cagliari, Italy, Sep. 2009, pp. 1–9.

[2] P. Christopher, "Geostationary satellite replacements with Brandon Molniya systems," presented at the Ka and Broadband Commun. Conf., Cagliari, Italy, Sep. 2009.

[3] G. P. Less *et al.*, "Efficient communications utilizing highly inclined, highly elliptical orbits," U.S. Patent 2004/0 211 864 A1, Apr. 25, 2003.

[4] D. J. Burnett, "Application of denali telecom LLC—Consolidated system proposal for authority to launch and operate thirteen satellites in the Pentriad system," US Federal Communications Commission, Denali Telecom LLC, Washington, DC, USA, Tech. Rep. IB Docket No. 01-96, Sep. 1997.

[5] D. Castiel *et al.*, "Application of virtual geosatellite LLC for authority to launch and operate the virtual GEO satellite system," US Federal Commun. Commiss., Virtual Geosatellite LLC, Washington, DC, USA, Tech. Rep. DA 06-2560, Jan. 1999.

[6] L. Wood, Y. Lou, and O. Olusola, "Revisiting elliptical satellite orbits to enhance the O3b constellation," *J. Brit. Interplanetary Soc.*, vol. 67, no. 3, pp. 110–118, Mar. 2014.

[7] L. Wood, "Internetworking with satellite constellations," Ph.D. dissertation, School Electron., Comput. Math., Univ. Surrey, Guildford, U.K., 2001.

[8] K. Fitchard. (Jul. 1, 2015). The crazy economics of inflight Wi-Fi. Fortune. [Online]. Available: http://fortune.com/2015/07/01/flight-wi-fi-travel/

[9] FCC Broad Band Progress Report. (Jan. 2016). *Federal Communications Commission FCC 16-6*. [Online]. Available: https://www.fcc.gov/reports-research/reports/broadband-progress-reports/2016-broadband-progress-report

[10] (2016). *Telecom Regulation Authority of India*. [Online]. Available: http://trai.gov.in/WriteReadData/WhatsNew/Documents/Press_Release_No_15.pdf

[11] J. Farrington, L. Philip, C. Cottrill, P. Abbot, G. Blank, W. Dutton. (2015). *Two-Speed Britain: Rural Internet Use. Aberdeen University Press*. [Online]. Available: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2645771

[12] Verizon. *State of the Market: Internet of Things 2016*. (2016). [Online]. Available: http://www.verizon.com/about/sites/default/files/state-of-the-internet-of-things-market-report-2016.pdf

[13] *Orbcomm Has 1.6 Million M2M Subscribers*, accessed on Jul. 23, 2016. [Online]. Available: www.orbcomm.com

[14] *Machine-to-Machine (M2M): Real-Time Fixed and Mobile IP Satellite Communications*, accessed on Jul. 23, 2016. [Online]. Available: https://www.viasat.com/services/m2m

[15] M. Collina, M. Bartolucci, A. Vanelli-Coralli, and G. E. Corazza, "Internet of Things application layer protocol analysis over error and delay prone links," in *Proc. 7th Adv. Satellite Multimedia Syst. Conf., 13th Signal Process. for Space Commun. Workshop (ASMS/SPSC)*, Livorno, Italy, Sep. 2014, pp. 398–404.

[16] Y. Kawamoto, H. Nishiyama, Z. M. Fadlullah, and N. Kato, "Effective data collection via satellite-routed sensor system (SRSS) to realize global-scaled Internet of Things," *IEEE Sensors J.*, vol. 13, no. 10, pp. 3645–3654, Oct. 2013.

[17] Z. Yue, W. Sun, P. Li, M. U. Rehman, and Z. Yang, "Internet of things: Architecture, technology and key problems in implementation," in *Proc. 8th Int. Congr. Image Signal Process. (CISP)*, Shenyang, China, Oct. 2015, pp. 1298–1302.

[18] S. Kraijak and P. Tuwanut, "A survey on Internet of Things architecture, protocols, possible applications, security, privacy, real-world implementation and future trends," in *Proc. IEEE 16th Int. Conf. Commun. Technol. (ICCT)*, Hangzhou, China, Oct. 2015, pp. 26–31.

[19] S. Raman, R. Weigel, and T. Lee, "The Internet of space (IoS): A future backbone for the Internet of Things?" *IEEE IoT Newslett.*, Mar. 2016, accessed on Jul. 23, 2016. [Online]. Available: http://iot.ieee.org/newsletter/march-2016/the-internet-of-space-ios-a-future-backbone-for-the-internet-of-things.html

[20] ViaSat, Inc. (Feb. 9, 2016). *ViaSat Unveils First Global Broadband Communications Platform to Deliver Affordable, High-Speed Internet Connectivity and Video Streaming to All*. [Online]. Available: http://investors.viasat.com/releasedetail.cfm?releaseid=954123

[21] *General Electric Predix Platform*, accessed on Jul. 23, 2016. [Online]. Available: https://www.ge.com/digital/predix

[22] U.S. Department of Transportation (US DOT). (Mar. 24, 2016). *2015 U.S.-Based Airline Traffic Data*, accessed on Jul. 23, 2016. [Online]. Available: http://www.rita.dot.gov/bts/press_releases/bts018_16

[23] A. Kossiakoff, W. N. Sweet, S. J. Seymour, and S. M. Biemer, *Systems Engineering: Principles and Practice*. Hoboken, NJ, USA: Wiley, 2011, pp. 139–164.

[24] M. Prior-Jones. *Satellite Communications Systems Buyers' Guide*, accessed on Jul. 23, 2016. [Online]. Available: http://www.scor-int.org/Working_Groups/satellite-systems-buyers.pdf

[25] A. Crisp, *M2M and IoT Via Satellite*, 6th ed. Cambridge, MA, USA: Northern Sky Research, Oct. 2015.

[26] A. Crisp. (Jan. 2016). The state of satellite M2M/Iot. SatMagazine. [Online]. Available: http://www.satmagazine.com/story.php?number=1897443442

[27] P. B. de Selding. (Nov. 10, 2015). *ViaSat Willing to Bet Big on Super-High-Throughput Satellites*. [Online]. Available: http://spacenews.com/viasat-willing-to-bet-big-on-super-high-throughput-satellites/

[28] P. Miller. (Aug. 2007). Ka-band-the future of satellite communication? Tele-Satellite.Com. [Online]. Available: http://tele-audiovision.com/TELE-satellite-0709/eng/feature.pdf

[29] M. Aloisio, P. Angeletti, F. Coromina, D. Mignolo, D. Petrolati, and E. Re, "A system study to investigate the feasibility of terabit/s satellites," in *Proc. IEEE 13th Int. Vac. Electron. Conf. (IVEC)*, Monterey, CA, USA, Apr. 2012, pp. 429–430.

[30] J. D. Gayrard, "Terabit satellite: Myth or reality?" in *Proc. 1st Int. Conf. Adv. Satellite Space Commun. (SPACOMM)*, Colomar, France, Jul. 2009, pp. 1–6.

[31] A. Kyrgiazos, B. G. Evans, and P. Thompson, "On the gateway diversity for high throughput broadband satellite systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5411–5426, Oct. 2014.

[32] A. Kyrgiazos, B. Evans, P. Thompson, P. T. Mathiopoulos, and S. Papaharalabos, "A terabit/second satellite system for European broadband access: A feasibility study," *Int. J. Satellite Commun. Netw.*, vol. 32, no. 2, pp. 63–92, Mar. 2014.

[33] P. Fines and A. H. Aghvami, "Fully digital M-ary PSK and M-ary QAM demodulators for land mobile satellite communications," *Electron. Commun. Eng. J.*, vol. 3, no. 6, pp. 291–298, Dec. 1991.

[34] R. F. Pawula, "On M-ary DPSK transmission over terrestrial and satellite channels," *IEEE Trans. Commun.*, vol. COM-32, no. 7, pp. 752–761, Jul. 1984.

[35] O. Yue, "Saddle-point approximation of M-ary phase-shift keying with adjacent satellite interference," *Bell Syst. Tech. J.*, vol. 59, no. 7, pp. 1139–1152, Sep. 1980.

[36] O. Vidal, G. Verelst, J. Lacan, E. Alberty, J. Radzik, and M. Bousquet, "Next generation high throughput satellite system," in *Proc. IEEE 1st AESS Eur. Conf. Satellite Telecommun. (ESTEL)*, Rome, Italy, Oct. 2012, pp. 1–7.

[37] E. Lutz, "Towards the Terabit/s satellite—-Interference issues in the user link," *Int. J. Satellite Commun. Netw.*, vol. 34, no. 4, pp. 461–482, Jul./Aug. 2016. [Online]. Available: http://dx.doi.org/10.1002/sat.1114

[38] J. Y. Suen, M. T. Fang, S. P. Denny, and P. M. Lubin, "Modeling of terabit geostationary terahertz satellite links from globally dry locations," *IEEE Trans. Terahertz Sci. Technol.*, vol. 5, no. 2, pp. 299–313, Mar. 2015.

[39] P. Narvaez, A. Clerget, and W. Dabbous, "Internet routing over LEO satellite constellations," in *Proc. 3rd Int. Workshop Satellite-Based Inf. Services (MobiCom)*, Dallas, TX, USA, Oct. 1998, pp. 89–95.

[40] E. Lutz, M. Werner, and A. Jahn, *Satellite Systems: For Personal and Broadband Communications*. Berlin, Germany: Springer-Verlag, 2000, p. 248.

[41] R. Sturdivant and E. K. P. Chong, "Systems engineering of low cost AESAs for high volume consumer LEO satellite ground stations," presented at the Ka and Broadband Commun. Conf., Cleveland, OH, USA, Oct. 2016.

[42] R. Sturdivant and M. Harris, *Transmit Receive Modules for Radar and Communication Systems*. Norwood, MA, USA: Artech House, 2015.

[43] A. Anton, R. Martinez, M. Salas, and A. Torre, "Performance analysis and implementation of spatial and blind beamforming algorithms for tracking LEO satellites with adaptive antenna arrays," in *Proc. 3rd Eur. Conf. Antennas Propag.*, Berlin, Germany, Mar. 2009, pp. 216–220.

[44] S. C. Ekpo and D. George, "Impact of noise figure on satellite link performance," *IEEE Commun. Lett.*, vol. 15, no. 9, pp. 977–979, Sep. 2011.

[45] B. Elbert, *Radio Frequency Interference in Communication Systems*. Norwood, MA, USA: Artech House, 2016.

[46] E. Ashford, "The future of satellite broadcasting systems," in *Satellite Communications in the 21st Century: Trends and Technologies*. Reston, VA, USA: American Institute of Aeronautics and Astronautics, 2003, p. 126.

[47] D. Geiger, "Another record year for silicon wafer shipments in 2015,"Semi.org. [Online]. Available: http://www.semi.org/en/another-record-year-silicon-wafer-shipment-volumes-2015.

[48] "GaAs wafer market to exceed 650M by 2017," *Semicond. Today*, vol. 7, no. 3, Apr./May 2012, accessed Jul. 23, 2016. [Online]. Available: http://www.semiconductor-today.com/features/PDF/SemiconductorToday_AprMay2012_GaAsWaferMarket.pdf

[49] M. S. Lam, A. Mukerjee, and M. Schroter, "Performance investigation of dual band millimeter wave SiGe low noise amplifier (LNA)," in *Proc. IEEE Int. Microw. RF Conf. (IMaRC)*, Hyderabad, India, Dec. 2015, pp. 258–261.

[50] S. P. Voinigescu *et al.*, "RF and millimeter-wave IC design in the nano-(Bi)CMOS era," *Si-Based Semiconductor Components for RF Integrated Circuits*, W. Z. Cai, Ed. Kerala, India: Transworld Research Network, 2006, pp. 2–29.

[51] T. Kanar and G. M. Rebeiz, "X- and K-band SiGe HBT LNAs with 1.2 dB and 2.2 dB mean noise figures," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 10, pp. 2381–2389, Oct. 2014.

[52] Y. S. Noh, M. S. Uhm, and I. B. Yom, "A compact Ku-band SiGe power amplifier MMIC with on-chip active bias," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 6, pp. 349–351, Jun. 2010.

[53] J. Andrews, J. D. Cressler, W. M. Lance Kuo, and C. Grens, "An 850 mW X-band SiGe power amplifier," in *Proc. IEEE Bipolar/BiCMOS Circuits Technol. Meeting*, Monteray, CA, USA, Oct. 2008, pp. 109–112.

[54] *Based on Quotations From Material Suppliers*, Microw. Packag. Technol., Inc., Fullerton, CA, USA, 2016.

[55] (Apr. 2011). *Technology Readiness Assessment (TRA) Guidance, US Department of Defense*. [Online]. Available: http://www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf

[56] *IEEE Standard and Definitions of Terms for Antennas*, IEEE Standard 145-2013, Dec. 2013, p. 16.

[57] J. M. Gomez, *Satellite Broadcast Systems Engineering*. Norwood, MA, USA: Artech House, 2001, p. 42.

[58] "Analysis of potential MVDDS interference to DBS in the 12.2–12.7 GHz band," Mitre Tech. Rep. MTR-01W0000024, Ap. 2001, p. 305.

RICK L. STURDIVANT (M'97) received the B.A. degree in religion from Vanguard University in 1986, the B.S. degree in electrical engineering from California State University at Long Beach in 1989, and the M.S. degree in electrical engineering from the University of California at Los Angeles in 1992. He is currently pursuing the Ph.D. degree in systems engineering with Colorado State University, Fort Collins, CO.

He is Founder and President of MPT, Inc. He co-authored the book *Transmit/Receive Modules for Communication and Radar Systems* (Norwood, MA, USA: Artech House, 2015), and authored the book *Microwave and Millimeter-Wave Electronic Packaging* (Norwood, MA, USA: Artech House, 2013). He serves on the IEEE MTT-12 Technical Subcommittee on Microwave and Millimeter-Wave Packaging and Manufacturing.

EDWIN K. P. CHONG (F'04) received the B.E. degree (Hons.) from the University of Adelaide, South Australia, in 1987, and the M.A. and Ph.D. degrees from Princeton University, in 1989 and 1991, respectively. He joined the School of Electrical and Computer Engineering with Purdue University in 1991, where he was named a University Faculty Scholar in 1999. Since 2001, he has been a Professor of Electrical and Computer Engineering and a Professor of Mathematics with Colorado State University. He has co-authored the bestselling book entitled *An Introduction to Optimization* (fourth Edition–Wiley-Interscience, 2013). He received the NSF CAREER Award in 1995 and the ASEE Frederick Emmons Terman Award in 1998. He was a co-recipient of the 2004 Best Paper Award for a paper in the journal Computer Networks. In 2010, he received the IEEE Control Systems Society Distinguished Member Award.

Dr. Chong held an IBM Fellowship with Princeton University. He was the Founding Chairman of the IEEE Control Systems Society Technical Committee on Discrete Event Systems, and served as an IEEE Control Systems Society Distinguished Lecturer. He is currently a Senior Editor of the IEEE TRANSACTIONS ON AUTOMATIC CONTROL and the IEEE Expert. He has also served on the Editorial Board of the *Computer Networks* and the*Journal of Control Science and Engineering*. He has served as a member of the IEEE Control Systems Society Board of Governors and as the Vice President for Financial Activities until 2014. He serves as the President-Elect. He was the General Chair for the 2011 Joint 50th IEEE Conference on Decision and Control and European Control Conference.

• • •