Virtual SATCOM, Skywave High-Frequency Communications at SATCOM Speeds Without Satellite Vulnerabilities

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Abstract: The US DOD needs a SATCOM alternative to mitigate the vulnerability of this critical infrastructure. The ionosphere is an underutilized channel path. It can be can harnessed to communicate at long range (3000 km) and high speeds (>32Mbps). It can service mobile users (e.g., DoD, maritime and aviation) using narrow beam apertures with wide bandwidths. For example; a base station in Guam, Hawaii, and California connects the Pacific Ocean from San Diego to China. An HF communications channel that can match the throughput of a SATCOM constellations at significantly reduce cost, without the vulnerability of satellite attack advances information technology. Current SATCOM systems are expensive and vulnerable; current HF systems are bandwidth limited and slow. This concept, employing narrow beams, avoids interference outside the beam and strong signal to noise (SNR) within the beam. Narrow beams at HF requires physically large antennas. Additionally, the beam must be electronically steerable to move with the ionosphere to service multiple mobile platforms. The architecture is similar to over the horizon (OTH) radar but applied to communication. It requires real time accurate knowledge of the ionosphere. OTH radars use ionosondes to see the best channel as the path flexes with the ionosphere.For communications, a worldwide, real-time, Internation Reference Ionosphere (IRI) database accessible to all, will incentivise adoption of this concept. Our research is using a ray tracing tool with IRI data to show high bandwidth availbity 24 hours per day. The key is visibility and capability (agility) to move the signals' frequency and azimuth of the base station as the channel path changes. Noise and multipath fading are issues, but agility and focused power negate the effect. If fielded, this system drives the need for real time IRI database. With additional research and development, this concept can compliment and reduce dependency on SATCOM communications.

Keywords— High Frequency (HF); communications; satellite communications; ionosphere; raytracing; digital modulation; OFDM; WBHF; UWB,

I. INTRODUCTION

Communication key to military operations. The DoD needs a SATCOM alternative. To date Skywave HF systems have not matched the capabilities of satellite systems. This proposed concept will deliver a high speed (>32 Mbps) High Frequency communications capability. It is an affordable and low-risk solution. The key is the removal of the physical satellite with its inherent vulnerability and high cost. The technical concept: active base stations used to focus High Frequency (HF) signals on mobile units, connecting mobile units to each other and other warfighting networks. By steering the beam, the base station can move the focused signal to service multiple users. Mobile units can communicate transhorizonaly (beyond line of sight (BLOS)) via the base station to relay digital networks and communications between mobile users and other ISR networks. To over-simply, the system operates much like a cellular architecture, but at a much greater range. The range from the base station to the mobile user is 3000 km (1620 NM). The high-gain base station's antenna increases the signal to noise ratio (SNR) at the receiver on both the forward link and backlink while preventing unintended interference to other users outside the narrow beam. Preventing unintentional interference is key to ultrawide bandwidth and ITU/FCC approvals. According to the U.S. Federal Communications Commission (FCC), ultra-wideband (UWB) refers to radio technology with a bandwidth exceeding the lesser of 500 MHz or 20% of the arithmetic center frequency; 20% of 15MHz is 3MHz. With high SNR and ultra-wide bandwidth, high-speed links (>32 Mbps) are possible. This speed significantly exceeds the current HF data link capabilities. Current HF Radio is very slow with standard rates around 1200 bits per second. Conceptually, a ground station in Hawaii, Guam, and California could service most of the Pacific Ocean, see Figure 1.

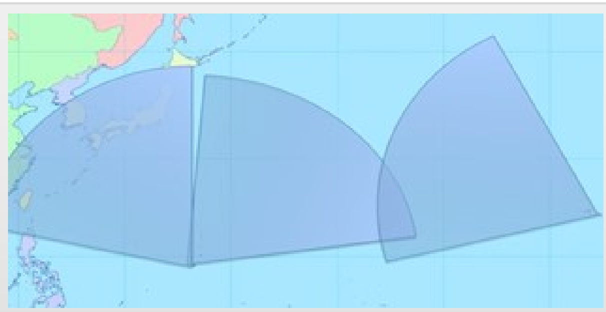

Figure 1. With ground stations in Guam Hawaii and California the Pacific is connected from the USA to China. Map is western Pacific from Hawaii to China with one base station in Hawaii and two in Guan.

The paper is organized into ten sections. Section I is an introduction. Section II describes the model. Section III discusses the communications protocol. Section IV discusses theoretical channel capacity. Section V discusses the ultra-wide bandwidth approach. Section VI is a discussion of the ionosphere and how rays are bent as they pass through the medium. Section VII is a discussion of the aperture that would be needed to meet the degree of beamforming required. Section VIII is a discussion of the protocol needed to cover the ultra-wideband signal. Section IX the results of modeling the system. Finally, Section X is the conclusions. **System Model**

This architecture has been coined "Spider Architecture" because the bent beams emanating from the base station resemble the legs of a spider and can be move as required to service the network of mobile users, see Figure 2. A large antenna at shore locations with a small antenna on mobile platforms provides the require SNR. Beams are moved from platform to platform to deliver or receive communication packets. The system must be agile to adjust to ionosphere perturbations. Beams on adversaries could jam or glean intelligence (SIGINT). Beams could be steered onto Ships, Aircraft, unmanned vehicles and SOF teams. The system has a low probability of detections and interception because the beam is directional with little power outside the focused beam. On the backlink, the mobile platform can transmit at minimum power to avoid detection while the high gain antenna can still detect the signal when forced on the mobile unit's location.

Essentially, this system trades omnidirectional, narrow bandwidth (slow links) for high-speed directional links. Current HF communication practice is 3 kHz bandwidth and 360-degree propagation, this new concept uses 3 MHz bandwidth (1000 time greater) with very narrow propagation angels (1-degree).

Because 3 MHz is a much more bandwidth than traditional HF communications, there needs to be a communication scheme that can efficiently multiplex date across this spectrum. Orthogonal Frequency Division Multiplex (OFDM) is a multiplexing scheme that can closely space many subchannels within the allowed bandwidth to efficiently move digital signals. OFDM breaks the bandwidth is to sub channels so data can be transmitted at a slower rate. OFDM with forward error correction (FEC) and interleaving can provide a reliable channel across an HF channel where multipath and interference are common.

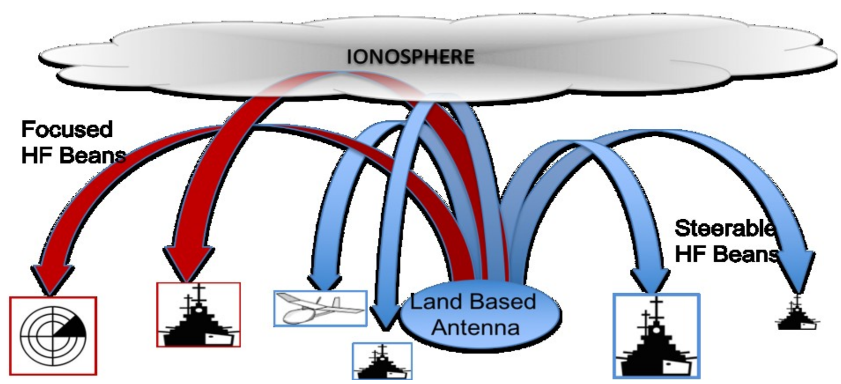

Figure 2. Spider Architecture. Focused beams from base station are bent by ionosphere to land on designated locations. Both friendly and adversary units can be serviced with network communications or electronic warfare (EW) techniques, e.g. jamming.

II. PROTOCOL CONSIDERATIONS

A. *OFDM can break a ultra-wideband digital channel into subchannels for transmission.*

The wireless communication industry is an example of how digital signal processing protocols and network architectures have made tremendous advances while using limited frequency allocations over less than optimum channel conditions to communicate at high speed. For example, Long-Term Evolution (LTE) uses Orthogonal frequency-division multiplexing (OFDM) as a method of encoding digital data on multiple carrier frequencies. OFDM divides high bandwidth inputs into narrower frequency subchannels so the frequency response of each sub-channel can be controlled to optimize throughput for each channel. OFDM is a particular type of frequency division multiplexing (FDM) where the frequencies of the subchannels are orthogonal to each other. Orthogonal signals can be packed close in frequency without subchannels interfering. This close packing allows more channels for a given bandwidth, hence more efficient use of the bandwidth. The subchannels transmit simultaneously. In other words, the high-speed serial date is converted into slower subchannels that are transmitted in parallel over the channels. The receiver decodes the slower subchannels and combines the data back into a high-speed serial channel, resulting is high-speed data.

OFDM was designed for non-ideal channels similar to HF propagation conditions. The frequency response of each sub-channel can be controlled to optimize throughput for each channel. Each sub-carrier is modulated with conventional modulation schemes like quadrature amplitude modulation (QAM) or phase shift keying (PSK) at low symbol rates. The key is the low symbol rate that results in low BER per subcarrier and high throughput when all the subchannels are combined into a high-speed data stream.

III. Channel Capacity

Theoretical channel capacity (C) [bps] is defined by the Shannon-Hartley equations (Equation 1). It is a function of the bandwidth (B) in Hz; noise power (No) in W/Hz; and power at the receiver (Pr) in W. The Friis transmission equation (Equation 2) models the power at the receiver. It is a function of the power transmitted (Pt) in W; gain of the transmitter and receiver (Gt and Gr) in dBi; wavelength (λ) in m; and range (R) in m, between the transmitter and receiver.

A. Shannon Hartley Equation

$$C = B\log_2(1 + SNR) \tag{1}$$

where

$$SNR = \frac{P_r}{BN_0}$$

B. Friis Transmission Equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{2}$$

Converting to decibels (dB)

$$Pr_{dB} = Pt_{dB} + Gt_{dB} + Gr_{dB} - P_L$$

$$P_{LdB} = 20\log\left(\frac{4\pi R}{\lambda}\right)$$

Table 1 lists the channel capacity for five different scenarios varying one of the input parameters. The range was 3,000 km for all scenarios. The power of the Tx and gain of Tx antenna are based on OTH radar data. Bandwidth and noise power are derived from our propagation path analysis and other studies of ionosphere conditions. Lower frequencies suffer less propagation loss, and the table uses the lower end and high end of the HF band. It is assumed that a 2 dBi dipole is utilized on mobile units. All scenarios experience better throughput at the lower end of the frequency range due to reduced free space path loss.

An additional advantage of the low power mobile Tx is that an adversary's HF Direction Finding (HFDF), and Signals Intelligence (SIGNIT) capability is reduced because the power of the signal is reduced. Another tactic is to use the high power directional base station as a jammer against adversary SIGINT and HFDF equipment to cover friendly communications. Because of directional beams, the jamming will not affect the communications, so simultaneous jamming and communications on the same frequency are possible.

Table 1 Channel Capacity

Scenario	C Mbps	B MHz	No dBw	Pt [W]	Gt dBi	Gr dBi	Freq MHz
Forward Link	58	3	-160	200,000	24	2	5
	42	3	-160	200,000	24	2	30
Back Link Tx=100W	25	3	-160	***100***	2	24	5
	9	3	-160	***100***	2	24	30
High Noise No= -140 dBm	38	3	***-140***	200,000	24	2	5
	22	3	***-140***	200,000	24	2	30
Low band width B=1 MHz	20	1	-160	200,000	24	2	5
	15	1	-160	200,000	24	2	30
Low Gain Gt=18 dBi	52	3	-160	200,000	***18***	2	5
	36	3	-160	200,000	***18***	2	30
Average	**31.8**						

IV. Bandwidth

The key innovations in the concept is the use of large amounts of bandwidth or ultra-wide band UWB applied to HF channels. Current HF systems operate in a band limited mode, typically 3-6 kHz.

A. New way of thinking about communications

To take full advantage of this channel path a paradigm shift is needed. The current policy of assigning fixed narrow band frequencies is not valid for this dynamic medium. To exploit this path, the communications operation must continuously adjust the operating frequencies in relation to the electron density to control the landing point of the refracted signal. This control requires the ability to see the ion concentrations and have the agility to change frequency if necessary to maintain high data rates. A real time IRI database might provide this visibility for many users. Currently, OTH Radar systems have a dedicated system of sounders to see real-time ionosphere conditions. With knowledge of the refraction angles, electronically steerable antennas can direct narrow beams of RF energy at the correct azimuth and elevation that will be received only by the mobile user at specific locations.

B. *Reverse Prizm Effect*

The ionosphere operates the same way that a prism works. Most have observed the effect of focusing a beam of white (multi-frequency) light onto a prism and watching the rays bent into different spectral frequencies and angles, i.e. red, green, blue, each at a different exit angle. In this application, to ensure the entire ultra-wide bandwidth transmission lands on a precise location, the signal must be separated into different frequencies and transmitted into the ionosphere at various angles to have all the rays diffract at their corresponding diffraction angle onto the intended user's location. Again, applying the prism phenomenon but in reverse: if different color (different frequencies) of light are pointed at various angles into a prism the output can be one multi-frequency white light at the desired angle.

Figure 3 illustrates two PHaRLAP generated views of rays transmitted from Old Dominion University over the Atlantic to a location 3000 km away. The bottom figure, at local noon, shows 134 different 100 kHz rays that arrive at the specified location. The top plot shows the same geometry at local midnight. The concentration of ions has changed, but there are still 69 rays that land at 3000 km.

V. Review of Ionosphere Ray Bending Process.

The ionosphere, roughly 85-1000 km above the earth, is sometimes referred to as "nature's satellite" because of the physical phenomenon of bending particular frequency radio waves back to the earth's surface.

Close to the earth's surface, below 85 km, the gasses in the atmosphere are continuously mixed by surface winds. In contrast, at higher altitudes (> 85km) there is little mixing, and the atoms and molecules become stratified due to gravity. Lighter gasses rise to the top and the heavier gasses "stack up" below. The atoms of some layers are more susceptible to ionization, for example, monatomic oxygen (O_1).

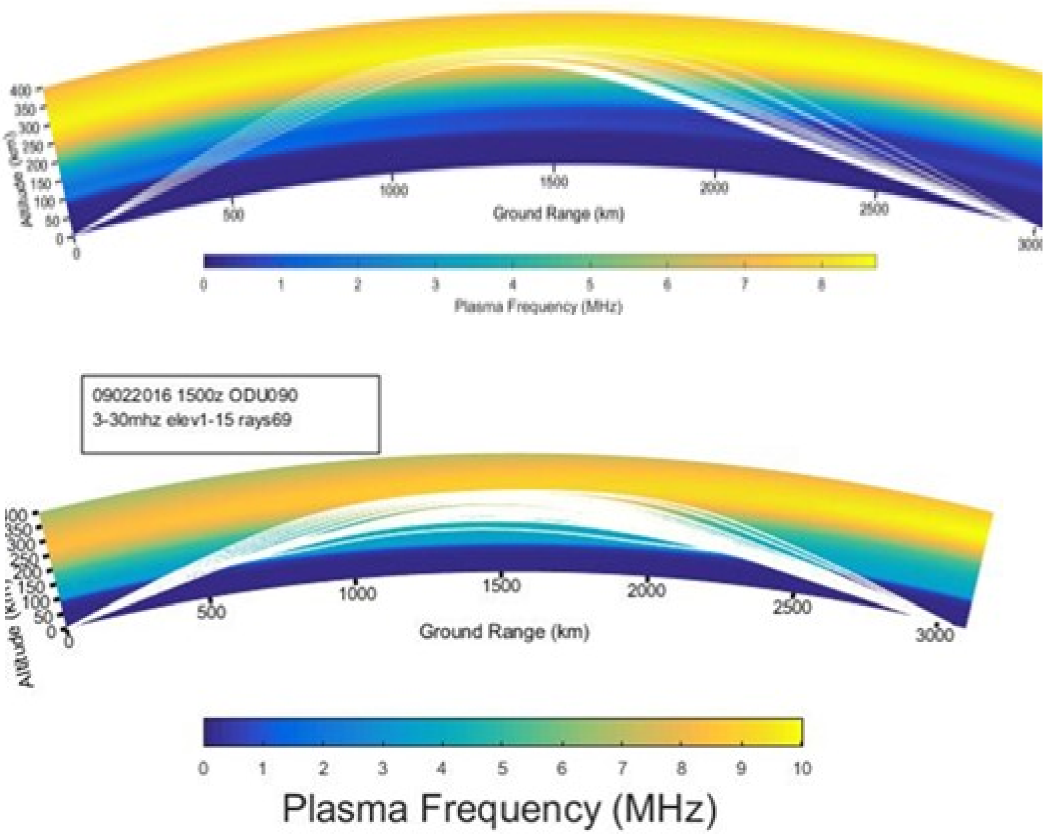

Figure 3 is a PHaRLAP plot that shows rays transmitted at different frequencies and elevations all "landing" at a precise predetermined location. The diagram also indicates the gradient of the ionosphere's plasma frequencies. The top graph is local midnight, and the lower graph is local noon. At night, the ion concentration is lower and at a higher altitude.

Ionization is the process where electrons are separated from atoms and molecules due to radiation from the sun. Once the electrons are freed, they react to the electromagnetic fields of communication signals, in other words, they propagate the energy of the communications signal similar to the way a copper wire propagates a signal through the metal. This propagation in the ionosphere only happens at certain frequencies, for example, HF.

In the HF spectrum, the communication signals are bent back to the surface. This only occurs when the free electron density is sufficient to bend a given frequency. The electron concentration slowly changes as a function of time of day, along with season and location. The degree of bending is a function of both the transmitted signal frequency and the critical frequency of the plasma referred to plasma frequency. The plasma frequency is a function of the electron density. Current HF systems using fixed frequency assignment encounter loss of service due to signal fading at that frequency. In this concept, the system will adjust channel frequency to achieve the long-range propagation without loss of service due to fading.

A. Free Electron Life Cycle

Free electrons are generated when atoms are ionized and then lost when recaptured by an ion. Generation only happens during the day. Recapture happens consistently and is a function of density in the layer. At higher altitudes, where density is less, it takes a longer period for recapture to take place.

During the day, the ionosphere is divided into four layers: D, E, F1 and F2 [2]. Lowest is the D layer at 85km, and highest is the F2 layer at approximately 350 km. When the sun sets, ion generation halts and the D layer quickly de-ionizes because atom density is greater. However, the F1 and F2 layers combine and stay ionized throughout the night due to the low density and resulting low probability of recombination. Therefore, the F has sufficient free electron density through the night to support communications. Our preliminary analysis has shown that the ionosphere can support ultrawideband communications 24 hours per day during all seasons of the year.

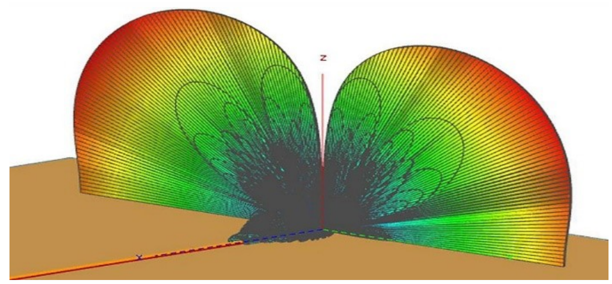

Figure 4: FEKO output of far field for 152 element HF array. This aperture has narrow azimuth focus and wide elevation focus.

VI. Aperture Considerations

A. Ionosphere Propagation Beams Through Space

This system requires aiming a beam at a precise location in space that results in the desired refraction back to earth landing at a particular location. This is how current OTH radar systems search for targets. The innovation leap here is the wide bandwidths require for high-speed data. Our initial research shows the channel through the ionosphere, can support the bandwidth required. If this system was deployed, mobile platform using currently fielded low gain antennas and selecting low power transmission could move a significant amount of data from mobile patrons to others via the base station. Consider the scenario of a UAV hundreds of miles from Naval units that need to transmit full motion video to human analysts. If a SATCOM link is not available, another relay path must be established. This virtual SATCOM system can follow the UAV and transmit the data to other mobile platforms. Because the signals are contained in azimuth and elevation beams, it will not interfere with other users of the same frequencies outside the beam. The system can time share the beam as required to reach different mobile or remote users.

B. Aperture

The best frequencies for refraction are in the HF range (3-30 MHz). Unfortunately, these frequencies have long wavelengths (100-10 m) which result in physically large apertures when narrow beam focusing is required. Example, nominal characteristics of representative skywave OTH radar systems in Australia and the US, achieves a 0.2 to 2-degree azimuth resolution using a 2.-3 km-long linear phased receiving array [3]. It is assumed that the mobile units, i.e. ships, aircraft and perhaps UAV would have relatively small size and low gain antennas due to the size constraint, so the gain must be built into the base station antenna. A high gain active electronically scanning array (AESA) technique could support maritime surface, aircraft and UAV customers simultaneously by timesharing the beam.

A robust software tool named FEKO is being used for antenna design. It is an Altair HyperWorks CAD product used in engineering design applications. This CAD software was specifically designed for electromagnet radiation aperture designs. Figure 4 is an example of a 152-element array aligned on an X axis. With this one-dimensional array, good azimuth is possible, but a two-dimensional array could provide both focused azimuth and elevation beams. Further analysis is needed to determine the optimum design for a phased array communications system. Though this shows linear array designs, other directional antenna array configurations could prove better suited for ultra-wideband requirements.

VII. Ionosphere Modeling Results

A. Propagation model of ultra-wide band channels

The Australian Defence Science and Technology Organization (DSTO) has developed an HF ray tracing toolbox called PHaRLAP in order to study the propagation of radio waves through the ionosphere. The 2-D raytracing engine is an implementation of the 2-D equations developed by Coleman [4], based on the Haselgrove equations [5]. The PHaRLAP model traces the signal's ray as it refracts through the ionosphere [6]. The refraction relies on the free electron density. The landing point depends on the degree of refraction (bending) and altitude of the bending. The PHaRLAP model calculates the ion density using data downloaded from the International Reference Ionosphere (IRI) database. The IRI is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) [7].

The IRI produces an empirical standard model of the ionosphere, based on all available data sources. For a given location, time, and date, IRI provides monthly averages of the electron density, electron temperature, ion temperature, and ion composition in the altitude range from 50 km to 2000 km. The data sources are a worldwide network of ionosondes, and incoherent scatter radars and instruments on several satellites.

Multiple rays at a position equate to multiple channels and sums to ultrawide bandwidth. Analysis of day/night and seasonal variations shows that sufficient bandwidth is available and will be discussed later in the paper.

B. PHaRLAP

The PHaRLAP model uses a MATLAB program to calculate the refraction of RF waves and plot the ray path. The tool takes IRI data and builds an electron density model, and calculates the plasma frequency for each element in the range-altitude grid for the location specified. It then, through incremental integration, calculates the ray path for a specified frequency given the locations, date, and time, and initial elevation and azimuth of the ray. The program begins with the initial coordinates (x, y, z) as the starting point. Using equation 3, the program calculates the group velocities at that point ($dx/d\tau$, $dy/d\tau$ and $dz/d\tau$).

With the position and velocity vector, the program calculates the next position. This iteration continues. Without the refraction ($d\chi/d\tau$) of the ionosphere, the ray would continue out into space. As the ray reaches the ionosphere, the ion concentration increases. The ions change the index of refraction for HF range frequencies. For these frequencies, the new index of refraction leads to a new wave normal angle, i.e. the wave has been bent. The wave velocity and angle lead to a new position. The program continues through this process calculating incremental changes until the wave reaches the surface or exits the grid.

This raytracing tool was developed by Dr. Manuel Cervera, of the Defence Science and Technology Office (DSTO), Australia. It has been used in many papers to estimate the performance of over the horizon radars (OTHR) and other projects. DSTO has developed the HF radio-wave raytracing toolbox (PHaRLAP) in order to study the propagation of radio waves through the ionosphere. PHaRLAP provides a variety of raytracing engines of various sophistication from 2D raytracing to full 3D magneto-ionic raytracing.

C. Basis of PHaRLAP model

The PHaRLAP model is based on the Hamilton principal. Dr. Jenifer Haselgrove was the first to derive the Hamiltonian ray tracing equations for HF radio waves through the ionosphere. These equations have been extensively used to study HF radio wave propagation and are the basis of the PHaRLAP program [4,5].

$$\begin{aligned} \frac{dx}{d\tau} &= \frac{c}{n}\left(\cos\chi + \sin\chi\frac{1}{n}\frac{\partial n}{\partial \chi}\right) \\ \frac{dz}{d\tau} &= \frac{c}{n}\left(\sin\chi - \cos\chi\frac{1}{n}\frac{\partial n}{\partial \chi}\right) \\ \frac{d\chi}{d\tau} &= \frac{c}{n^2}\left(\cos\chi\frac{1}{n}\frac{\partial n}{\partial z} - \sin\chi\frac{1}{n}\frac{\partial n}{\partial x}\right) \end{aligned} \tag{3}$$

Where χ is the angle between the wave normal and the respective axis; c is the speed of wave propagation in a vacuum, and n is the refractive index.

The PHaRLAP program divides the area of interest into a grid based on the input range (x) and the altitude range (z). Next, the plasma frequency is calculated based on the IRI date for the date and time to be modeled.

D. Experimental Results

In this analysis, a fan of rays: at frequencies between 3 and 30 MHz (100 kHz increments); and from 1 to 15 degrees' elevation (1-degree increments) were input into the model. The start location was Old Dominion University in Norfolk VA. with an azimuth bearing of 090 degrees, (east). The program was modified looking for rays that landed at a particular range (3000 km) and recorded their launch frequency and elevation angle. For example: if a ray transmitted at 6 degrees of elevation and 17.2 MHz returned to the surface at 3000 km ±50 km then that ray was recorded.

The total number of rays that met this test on the specified date and time is recorded in Table 2. The program was run 24 times, once for each hour of the day. The program was run on four different days to show the seasonal effects. The results can be seen in Figure 5. The data clearly shows:

- There are numerous rays available 24 hrs per day. Day hours have more rays than night hours.
- Summer has a higher number than winter hours.
- An average number of rays was 64 which is equivalent to 6.4 MHz of bandwidth.
- Only a few hours (7) are below 20 rays.

If each ray was 100 kHz, a rough approximation of bandwidth could be determined. Figure 5 plots the number of rays vs. the hour. The number of rays peaks out at local noon, but even at night the number of rays usually exceeds 50 rays or 5 MHz of bandwidth.

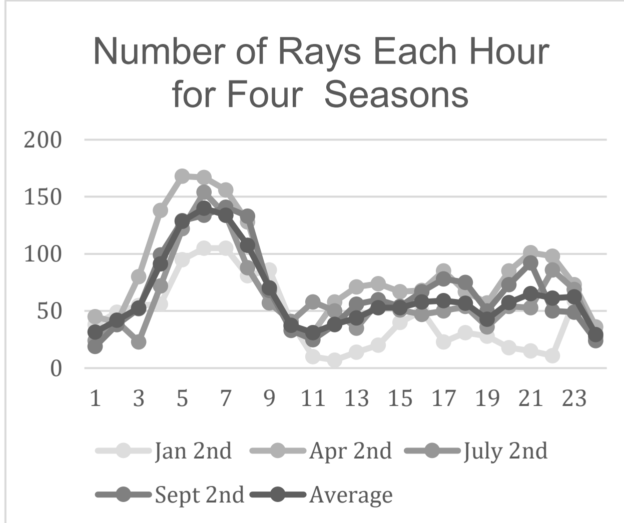

Figure 5. Shows the number of rays, at different times, on four different days in winter, spring, summer, and fall of 2016. Transmitted from Old Dominion University that will land on a target 3000 km to the east

VIII. Conclusion and Further study

The ionosphere is capable of supporting multiple frequencies and paths that could be used for long-range cellular communications. The ionosphere's frequency response varies in time, so frequency agile systems are needed to follow the ion variations at the plasma frequency rate of change. An infrastructure like the IRI could provide timely visibility of which frequencies are available at a given time to support high data rate digital communication.

Antenna systems must be analyzed to find the best configuration that can meet the frequency agility and bandwidth requirements. How precise and what gain can be expected. Better modeling of the communication channel is needed better define the bandwidth limits.

Table 2 Number of Rays

Time of Day		Table 2 Number of Rays				
UT Hour	*Local Hour*	*Jan 2nd*	*Apr 2nd*	*July 2nd*	*Sept 2nd*	*Average*
0	5	38	45	24	19	31.5
1	6	49	40	41	38	42
2	7	55	80	23	52	52.5
3	8	56	138	72	99	91.25
4	9	95	168	122	129	128.5
5	10	105	167	154	134	140
6	11	105	156	134	141	134
7	12	81	128	88	133	107.5
8	13	86	70	57	68	70.25
9	14	40	36	41	33	37.5
10	15	10	31	58	25	31
11	16	7	58	50	38	38.25
12	17	14	71	35	56	44
13	18	20	74	58	60	53
14	19	40	67	51	54	53
15	20	50	68	47	67	58
16	21	23	85	50	78	59
17	22	31	67	54	75	56.75
18	23	28	57	36	50	42.75
19	0	18	85	54	73	57.5
20	1	15	101	53	92	65.25
21	2	11	98	86	50	61.25
22	3	59	73	69	49	62.5
23	4	31	36	27	24	29.5

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The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research and the International Union of Radio Science. It is the international standard empirical model for the terrestrial ionosphere. Please see the IRI websites http://irimodel.org and http://IRI.gsfc.nasa.gov for further detail.

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