Reliable Millimeter Wave Satellite Communication with Transition to Lasers

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***Abstract*—Reliable millimeter wave satellite communications are discussed with only modest site separation and switched diversity. Furuhama rain correlation functions show that a mere 8 km site separation will allow nearly independent rain results. Most 30 GHz ground stations may expect 99.9% link reliability with dual sites. Satellite laser communication may use a larger site separation with a Boldyrev cloud correlation function and Brandon satellite orbits.**

***Index Terms*—Brandon Molniya orbits, diversity, millimeter wave communication, rain correlation function.**

I INTRODUCTION

THE benefits of millimeter wave satellite communication systems, especially in the 30-49 GHz region, have been examined extensively for the past three decades [1] and intensively followed for over a decade [2,3,4]. Many satellite engineers remained hesitant in specifying Ka band (as 30 GHz) or higher millimeter wave systems because rare, intense rains would disable the systems. We discuss the value and power of the Furuhama [5] rain correlation function here, and show that dual ground sites separated by 8 km *would readily offer 99.9% availability* even in difficult areas like Miami. We then indicate that most other areas of the US would readily support frequencies higher than Ka band.

Very high levels of rain attenuation can occur on single links in some areas of the US. Integrated gaseous attenuation suitable for space-ground links is included in Fig. 1-1, as opposed to terrestrial attenuation of ITU analysis. Nearly 50 dB attenuation is indicated at 30 GHz for this intense 35 mm/hr rain rate at Miami, with a modified Crane rain model [6]. Fig. 1-1 shows the rain loss at higher frequencies becomes prohibitive at 99.9% reliability, where almost a 25 dB deficit is seen at 30 GHz v. 14 GHz.

The intense 30 GHz attenuation at Miami may also be estimated for other parts of the US by using the cloud attenuation function, and checking at other key sites as New York City. The result is Fig. 1-2. Very intense attenuation regions are seen in the Northern Hemisphere and near New Guinea.

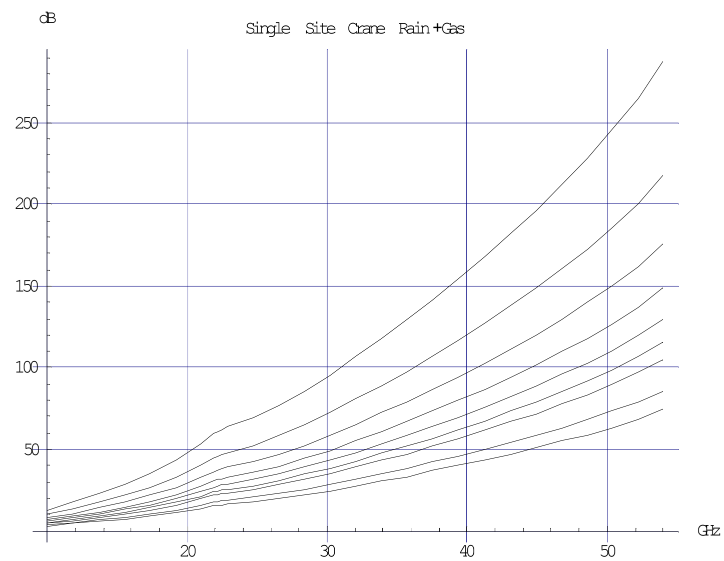

Fig. 1-1 Crane Rain+Gas Attenuation; Miami 99.9% Availability;35mm/hr MathematicaJun1—C.nb .

The single link attenuation at 30 GHz over the Northern Hemisphere as Fig 1-2, is seen with 3D attenuation over the contours of the land masses.

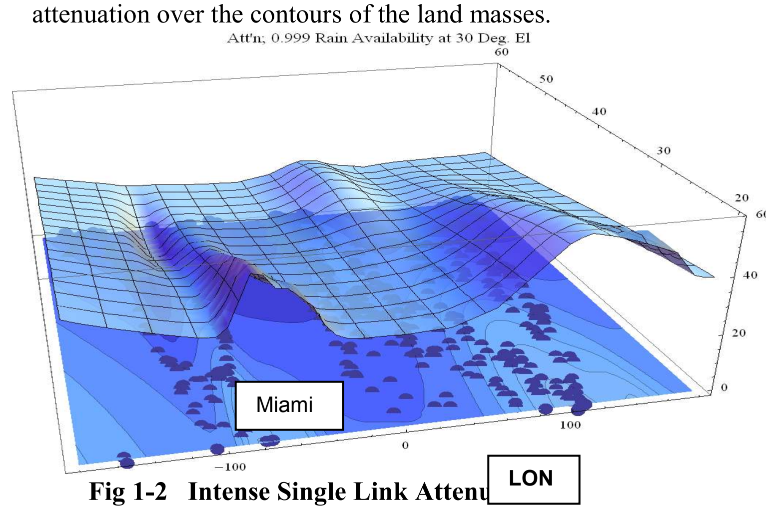

Fig 1-2 Intense Single Link Attenu Estimates at 99.9% Availability; 30 GHz
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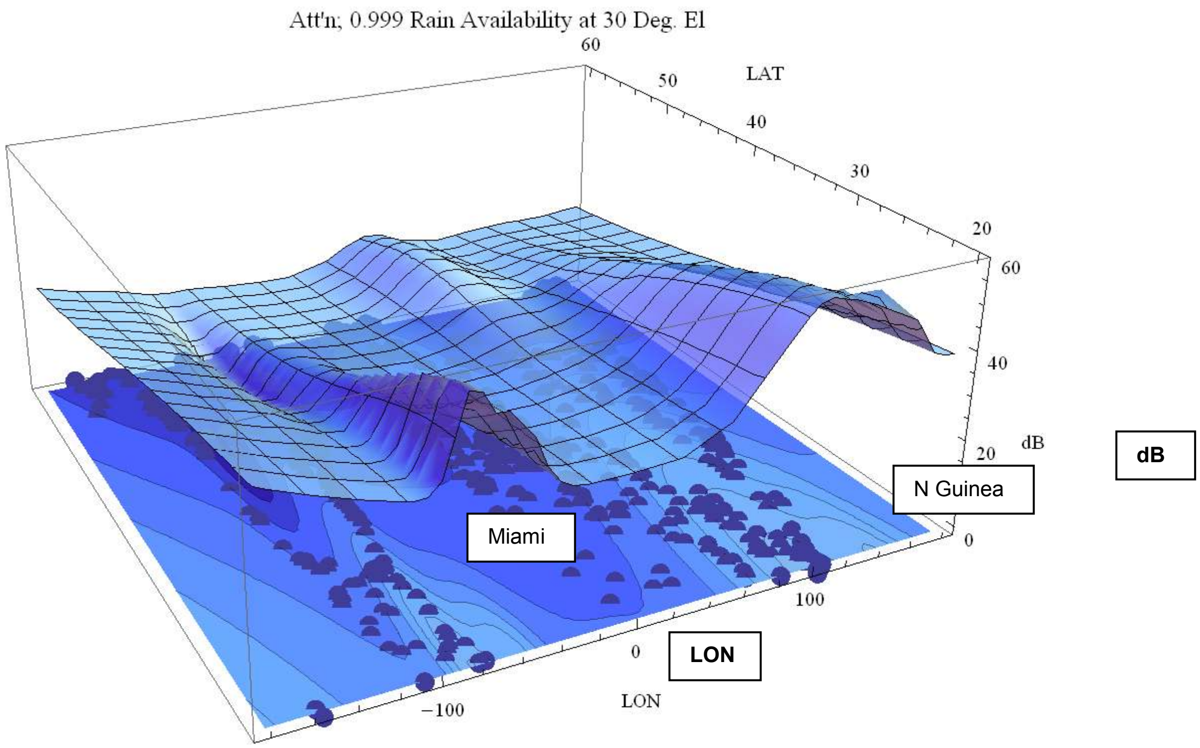

Fig 1-2 Intense Single Link Attenuation Perspective at 99.9% Availability; 30 GHz

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This intense single link rain attenuation at 30 GHz at 99.9 % availability can be sharply reduced by noting Furuhama's rain correlation function. It drops to only 0.2 at ground site separation of only 8 km, or site diversity would be expected to have almost the full benefits of independence. A derivation of the net attenuation for switched diversity may be found [7]. The benefits of separated ground sites may be found by a double integration of a bivariate exponential function.

The cumulative distribution for the minimum attenuation at 2 sites with correlation ρ and S.D. β is:

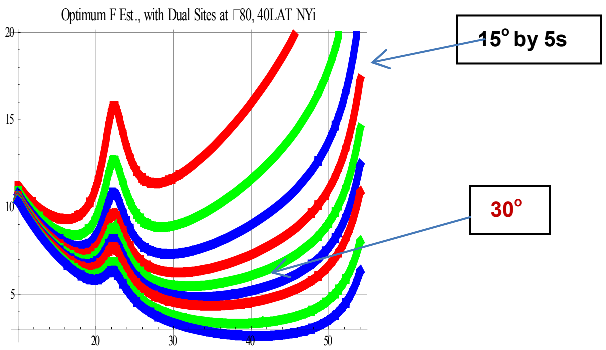
$$P[A1>AR,A2>AR]=\frac{e^{-\frac{AR\left(1+\frac{1}{\sqrt{1-\rho^2}}-\frac{\rho}{\sqrt{1-\rho^2}}\right)}{\beta}+\frac{\lambda+\beta\,Log[\phi]}{\beta}+\frac{\lambda+\beta\left(1-\sqrt{1-\rho^2}\right)+\beta\,Log[\phi]}{\beta\sqrt{1-\rho^2}}}}{1-\frac{\rho}{\sqrt{1-\rho^2}}} \qquad (1)$$

The net rain attenuation probability AR may be found to be much lower than single link attenuation at low correlation ρ.

We also include a gain advantage on higher frequencies. The gain at constant aperture increases as frequency squared. This is important because ground system cost is strongly related to antenna aperture. Rather than being simply concerned with atmospheric loss as Figs. 1-1 and 1-2, we include loss with performance at constant cost, and use a Net Loss term,

Where Net Loss = Loss - 20 Log[10, fGHz] dB (2)

fGHz= frequency in GHz



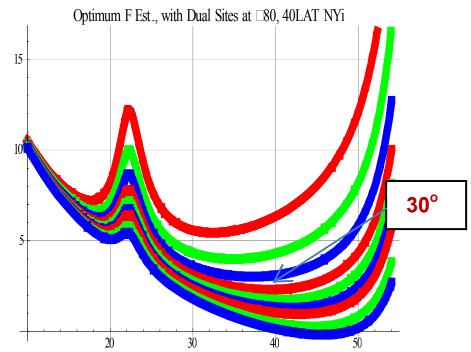


Fig 1-3a Net Loss at Miami
Site Diversity 8km
35 mm/hr; 99.9%

Fig 1-3b Net Loss at New York
Site Diversity 8km

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The minimum Net Loss at Miami can be found to be very close to 30 GHz (30.8 GHz) for 8 km site separation, as needed for 0.2 site correlation by Furuhama's rain correlation function. This may be interpreted as an optimum frequency for 99.9% availability is required and if site diversity is available. The 30 degree elevation angle chosen can often be met with appropriate satellite systems.
The minimum Net Loss moves to over 40 GHz for the lower rain rates at New York.

These optimum frequencies can be examined over the entire continental US, and an approximate fit can be derived as Fig 1-4 . Optimum frequencies greater than 40 GHz are indicated for Boston, and frequencies approaching 45 GHz in southern Canada. Three dimensional features can be added to the optimum frequencies for another view, as Fig. 1-5.

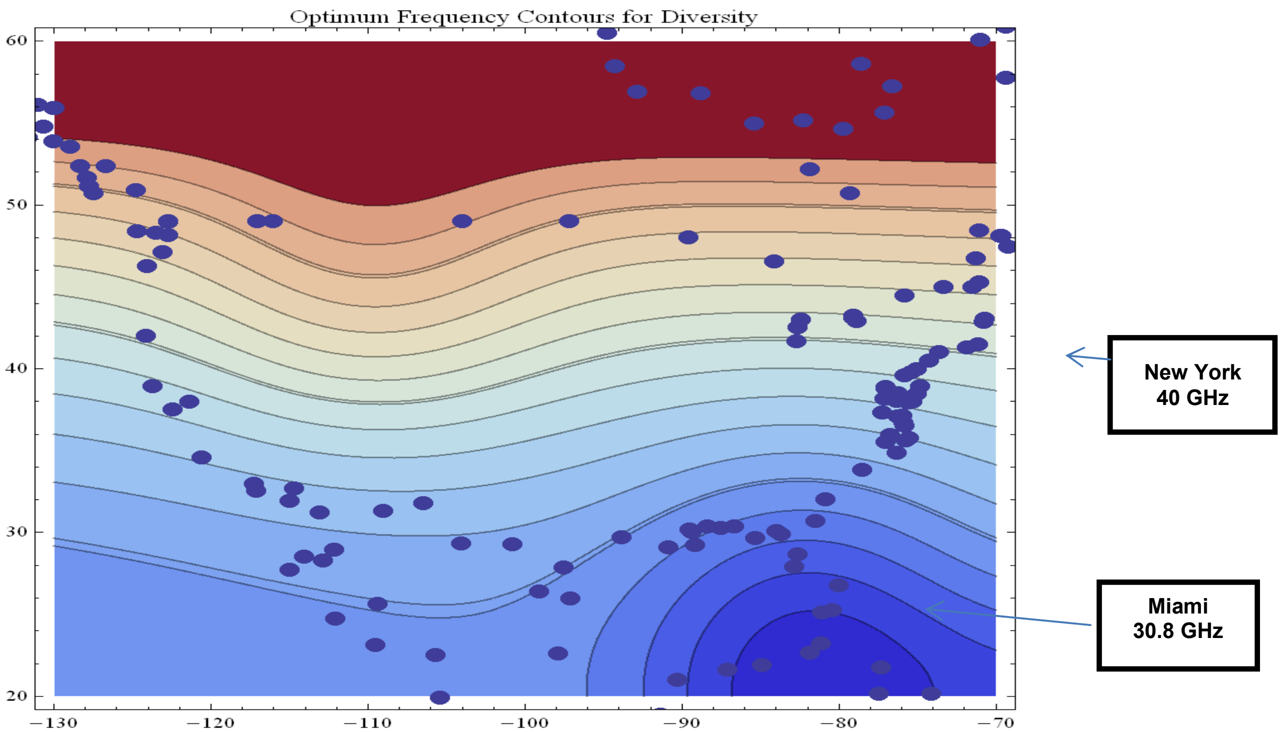

Fig 1-4 Optimum Frequency Trends with Furuhama's 8 km Site Diversity
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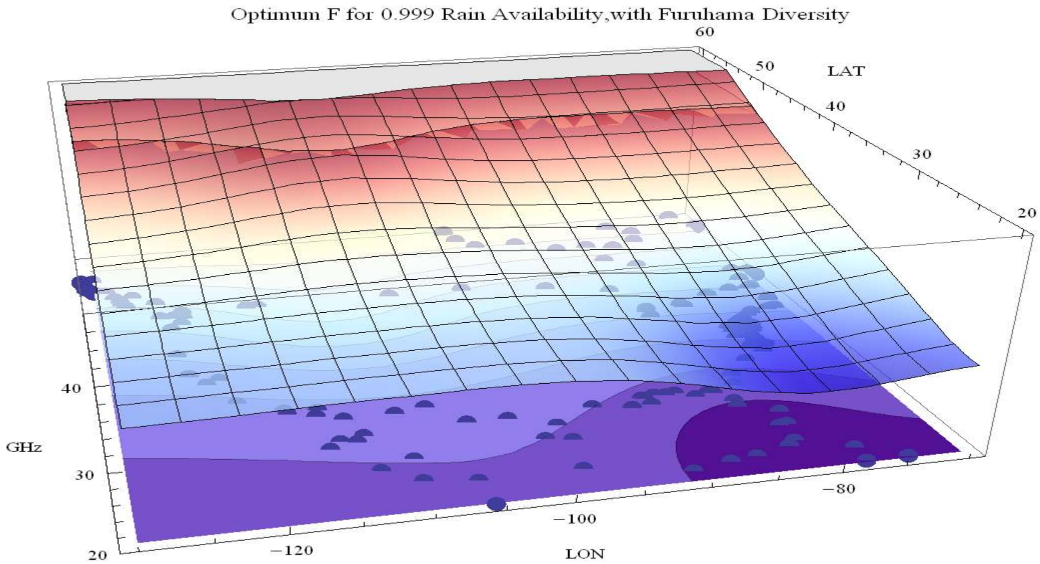

Fig. 1-5 Optimum Frequencies over US with 3D and Contours
Dual Site Separation 8km
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II. LASER SATELLITEWITH BRANDON ORBITSFOR HIGH ELEVATION ANGLES

The late W.T. (Bill) Brandon recognized the value of dynamic satellite systems, and he also recognized the need for simple, low cost, high gain ground antennas. He was intrigued with the easy ground tracking of a select group of Molniya satellite systems [8]. Fig. 2-1 shows a selected Brandon Four satellite system. We apply the Brandon4 here to laser satellite communications.

The Appendix shows the Brandon 4 advantages as an effectively stationary satellite, while giving high elevation angles and low attenuation in the prime North Temperate Zone..

Cherkaoui et al [9] have proposed another excellent variation of a Molniya system at the Ka Conference in Milan. It will give outstanding coverage of the Arctic regions, and it will also give good coverage in the temperate zone.

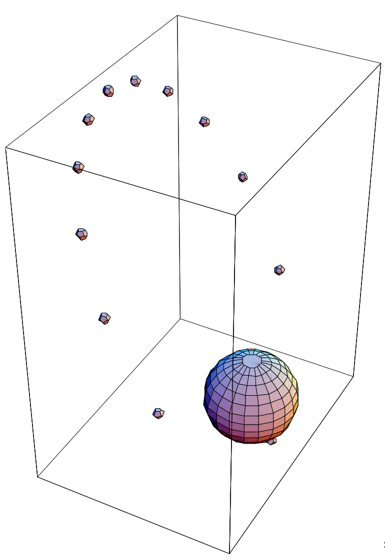

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Fig. 2-1a First Brandon Plane,with One Hour Snapshots

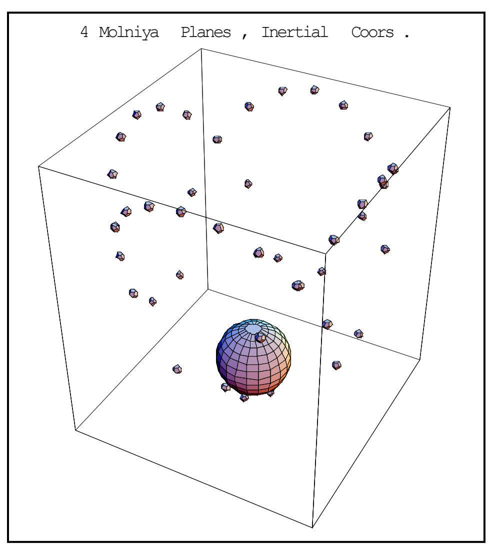


Fig 2-1b Four Brandon Planes for Stationary Ground Antennas

Brandon's dynamic satellite interests included other selected Molniya eccentricities which could offer high gain with very simple ground systems. One of Brandon's Molniya system interests is shown in Fig. 2-1, with 0.722 eccentricity for a high gain Brandon ground antenna.

Brandon orbits allow high elevation angles in the temperate zone north of Washington, DC. This will be a special advantage for low cost (but high atmospheric loss) laser satellite communications. We do thorough examinations of the worldwide elevation angles at all times and places, and construct probability density functions (pdf) for elevation at each latitude. We then reduce the pdf to a function for all latitudes, and show the pdf in 3D plots.

W.T. Brandon also had other important satellite interests. The Brandon6 (a 6 satellite system with e=0.729) allowed even higher gain stationary ground antennas. The Brandon6 constellation required Right Ascensions spaced at 60 degrees, and 4 hour handovers. The Brandon constellations not only offered low attenuation and higher performance than geostationary orbits in the Northern Temperate zone, but also the orbits were self cleaning. The satellites had a natural lifetime as 1-3 decades, as opposed to Millennia for geostationary orbits.

The Brandon orbits are especially valuable for higher values of atmospheric attenuation, such as satellite-ground laser communication. The high elevation angles in the temperate zone can sharply reduce observed attenuation for large population centers as New York, Ottawa, Moscow, Berlin, and Stockholm.

10 Micron Attenuation at 80% Availability

Zenith attenuation, as Fig 2-2, may be found from [2] and Chu and Hogg [10] is used here to find Brandon4 attenuation.The Brandon orbits allow attenuation even lower than zenith, at temperate latitudes with a square ground array [11, 12] as in Figs. 2-3, -4. The correlation for the ground stations is found from Boldyrev[13].

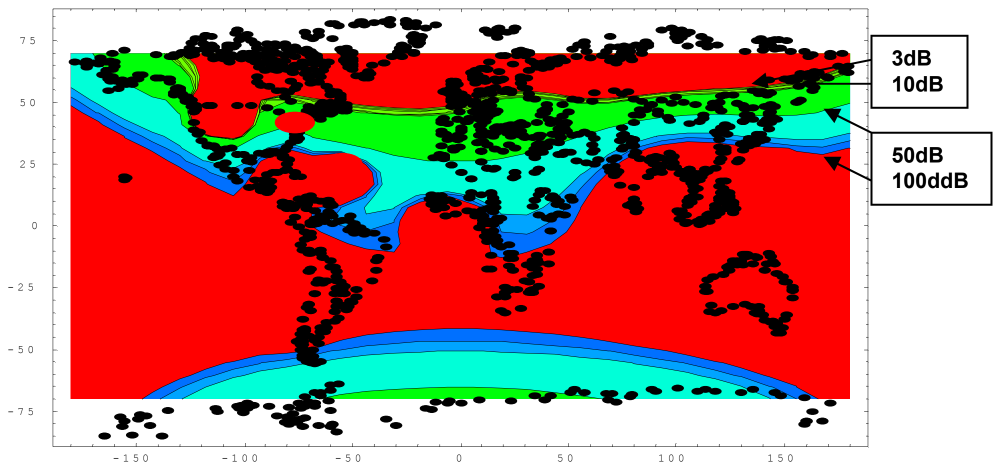


Fig 2-2 Zenith Attenuation with Fine Detail 3,4,5,6 dB Contours at Labrador 80% Availability Mathematica Jun28—80PC.nb

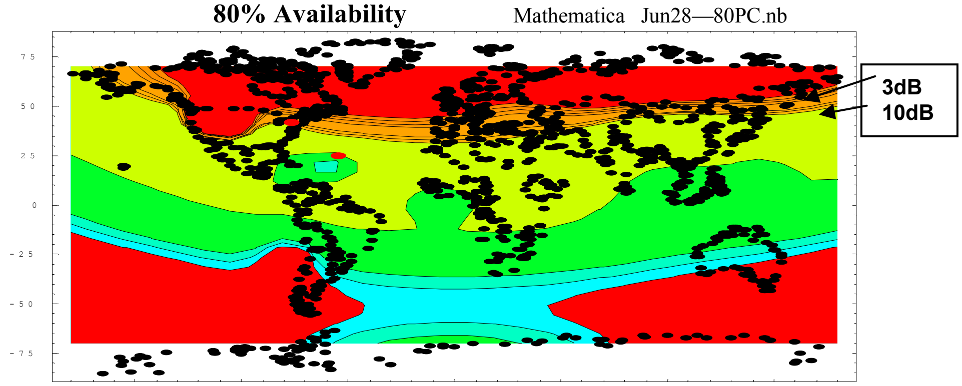


Fig 2-3 Brandon4 Attenuation with 8,9,10 dB Contours at Washington Quad Diversity, 160 km Square Array Mathematica Jun28Apr20—80PC.nb

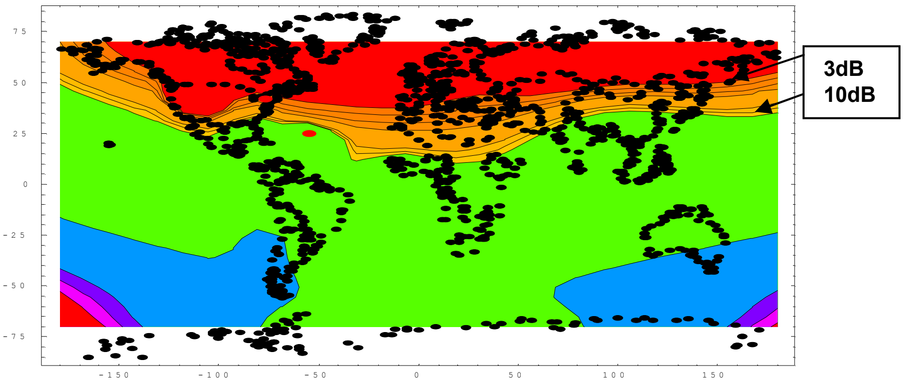
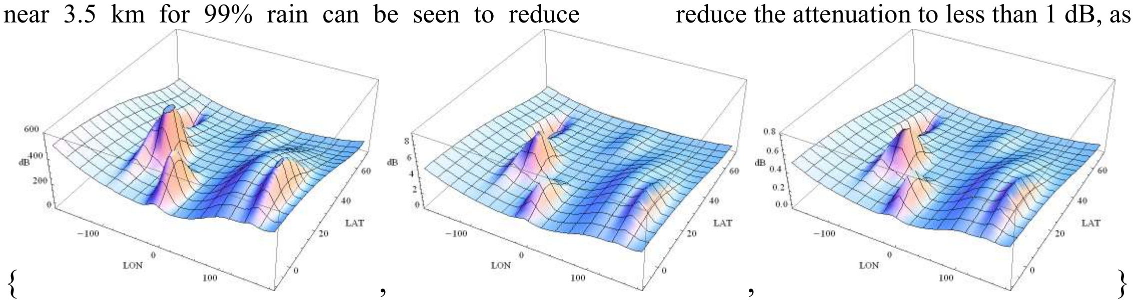


Fig 2-4 Brandon4 Attenuation with 4 dB Contour at Washington; 360 km Quad Mathematica Jun28Apr20—80PC.nb

Higher altitude receivers can enjoy good reliability with minimal attenuation. The Crane cloud height at near 3.5 km for 99% rain can be seen to reduce worldwide zenith attenuation from 600 dB to the order of 8dB. Altitude of 4.3 km is indicated to reduce the attenuation to less than 1 dB, as Fig 2-5.



Ground **3.5 km Altitude** **4.3 km Altitude**

Fig 2-5 Worldwide Attenuation at Ground Level, 3.5 km, 4.3 km for 10 Microns For 90% availability, Single Link

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III CONCLUSIONS

We indicated sharp relief for reliable millimeter wave satellite communication links with modest 8km site diversity.Furuhama's rain correlation function was so helpful, that even a few kilometers site separation could offer good link relief at 99.9% reliability. We saw that Furuhama's rain correlation function can allow sharp reductions in attenuation and corresponding greater reliability for frequencies higher than 30 GHz. Fig 1-4 indicated optimum frequencies at constant aperture near 40 GHz at New York City and 99.9% reliability.

This high reliability for millimeter wave systems required ground elevation angles near 30 degrees for short atmospheric paths, and low atmospheric loss. Geostationary satellites may not always allow high elevation in the Temperate Zone (e.g., New York City). We showed the high elevation angles available with Brandon Molniya satellites (Appendix) with the convenience of stationary ground antennas.

Brandon orbits with select Molniya eccentricity were seen to offer availability over 80% with 10 micron satellite communication for Canada, the Rockies, and Scandinavia. Ground site diversity, with large separations dictated by Boldyrev's cloud correlation, allowed attractive ground sites at New York City, as Fig. 2-4. Very low 10 micron attenuation was indicated for satellite- aircraft links at 3.5 km and above in Fig 2-5.

IV ACKNOWLEDGMENTS

Dr. P K Lee of the MITRE Corp offered early insights into the reliability of Ka band satellite-aircraft links. His extraordinary insights into Ka band reliability included the benefits of Ka band during ionospheric scintillation. Hal Gershman had fruitful studies of millimeter wave power sources.

Sal Mangione, at a Wolfram Research conference in Champaign Illinois, showed that combined 3D and contour plots can be very helpful.

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Appendix Brandon Molniya Orbits for High Performance, Stationary Convenience

The Brandon Molniya orbits show two (nearly) stationary points from the ground station's viewpoint. These stationary points are continuously occupied with the four phased Brandon4 satellites. The Brandon satellites are used here to introduce relatively low attenuation in a realistic worldwide laser satellite communication system. Fig A-1 shows the stationary points from the standpoint of the ground station.

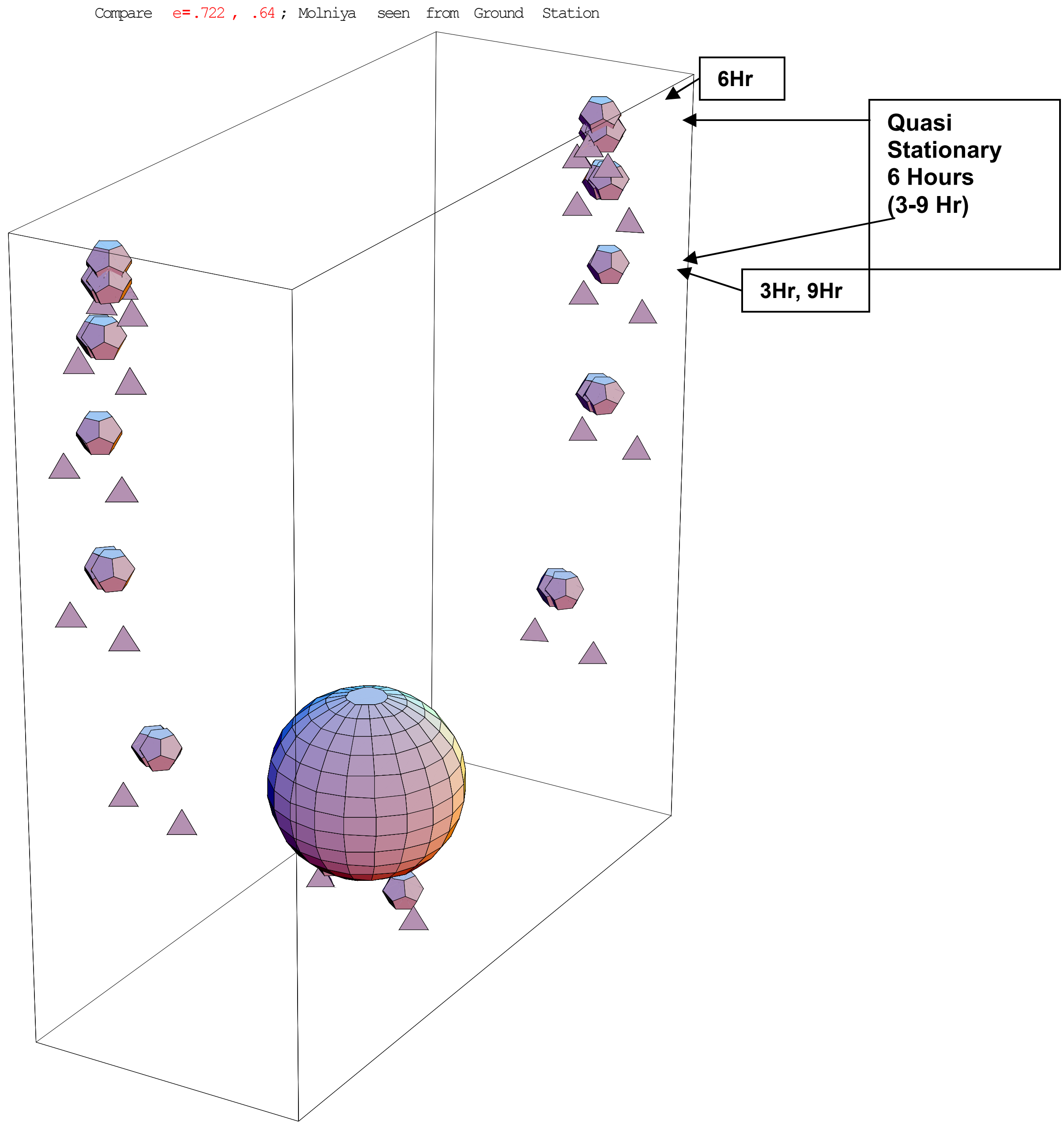

Fig A-1 Brandon Molniya Orbit as Seen from Ground Site; e=0.722
Note Stationary Effect for 6 Hours at Apogee

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The Brandon orbits offer excellent elevation angle for the northern temperate zone, and relatively low atmospheric attenuation for satellite –ground laser links. The elevation angles can be extensively calculated, and a probability density function for elevation can be found as a function of N Latitude. Hundreds of thousands of elevation calculations for all times and places can finally yield a continuous pdf with Gaussian fits at each latitude.

The pdf for elevation *for all time and locations* can be plotted as Fig. A-2, where the 3D figure has elevation to the right and Latitude into the page.

The long 3D function for elevation has sections which are closely Gaussian, with mean elevation 63.2 degrees and standard deviation 13.6 degrees at *60N Latitude (Gaussian[63.2,13.6])*. Analogously, New York City at *40N Latitude* has properties as *Gaussian [52.3,11.1], and Jacksonville at 30N is closely Gaussian[49.8,8.4]*.

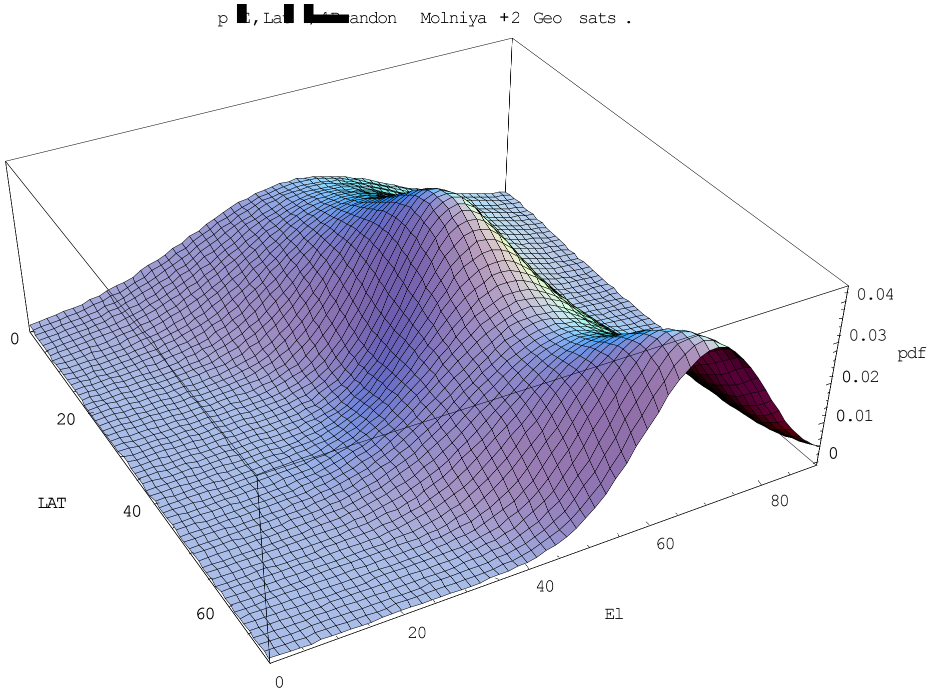

Fig. A-2 Elevation pdf for Brandon4 Plus 2 Antipodal GEO