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Paper Session I-B - Laser Communications Utilizing Molniya Satellite

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Laser Communications Utilizing Molniya Satellite

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The telecommunications evolution has advanced to level where bandwidth is now a limiting factor for data transmission. The use of laser communications with satellites is not a new idea and has been proven ,Ref [3], in certain configurations using geostationary orbits. The purpose of this thesis is to explore the use of laser technology for land based terminals above the 80-degree latitude. After establishing an understanding of the nature of the mathematical model for the turbulent effects on laser beams, the investigation will utilize the Molniya satellite orbit characteristics with the goal of eliminating or reducing the tracking complexity.

In the RF application, various satellite orbits have been utilized for communications that would otherwise be impossible using traditional ground based stations. The High Earth Orbits (HEO), Earth Geostationary and Molniya, offer the greatest coverage and flexibility. The RF band antenna can be either omni-directional or focused. An omni-directional antenna is ideal where the space-based transceiver can be anywhere. This is apposed to a focused antenna that must have apriori knowledge of the intended space-based transceiver station's location.

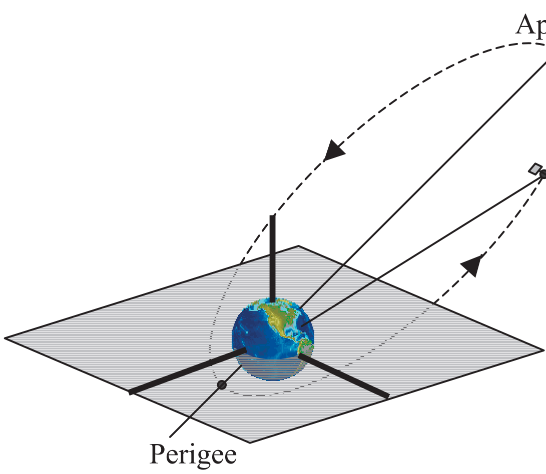

Figure 1 – The Molniya Orbit

Laser energy is inherently focused requiring extra design considerations. For laser applications the atmosphere creates a pejorative effect in the form of scintillation. A Geostationary Earth Orbit (GEO) can be effectively viewed from a ground station, for RF communications, up to latitudes of, approximately, 81.3 degrees. However, for a space-based optical transceiver, orbiting geostationaryly, a ground-based link must be positioned in the lower latitudes to minimize the length that the beam must travel through the lower turbulent atmosphere, thus minimizing the effects of scintillation. A geostationary satellite, by definition, remains in the same position in the sky, relative a ground station. This makes one of the most important advantages of this system being no tracking equipment necessary. Therefore, once the laser is aimed correctly it is set for operation on a 24-hour basis. This benefit can be extrapolated to the development of very portable ground transceiver. However, what can be done to provide geostationary communications in higher latitudes?

The Atmosphere as a Medium

Light can be completely blocked by moisture in the form of clouds and precipitation and can, therefore, be disturbed by the refraction effects of air turbulence. For the purposes of the model chosen here, only clear-air with turbulence is considered.

Kolmogorov developed a mathematical model to describe turbulence based on velocity variations. Here we assume the index of refraction fluctuations are due to temperature differences in the air. We then assume that the temperature differences are mixed by the velocity fluctuations. This means that the index of refraction fluctuations follow the same behavior as defined by Kolmogorov in the development for velocity fluctuations described by:

$$< \left(n(r) - n(0)\right)^2 >= C_n^2 r^{2/3} \tag{1}$$

The refractive index structure constant has the unusual dimension of meters$^{-2/3}$ and can range from 10^{-17} m$^{-2/3}$, for weak turbulence, to a high end of the scale 10^{-13} m$^{-2/3}$, for strong turbulence. These values also roughly correspond to late night and mid-day times respectively. The refractive index structure constant, C_n^2, is a constant, however, for cases where the laser path is not horizontal C_n^2 is no longer a real constant but changes relative to altitude. For the analysis presented here the Hufnagel-Valley (H-V) model of the structure constant is described by [1]

$$
\begin{aligned}
C_n^2(h) = {} & 0.00594(v/27)^2(10^{-5}h)^{10}\exp(-h/1000) \\
& + 2.7\times10^{-16}\exp(-h/1500) + A\exp(-h/100)\,,
\end{aligned}
\tag{3}
$$

where h is altitude in meters, v is the rms wind velocity in meters/second, and A is a chosen empirical value of C_n^2 at the ground, more correctly notated $C_n^2(h)$.

For $\dfrac{1}{L_0} \ll \kappa \ll \dfrac{1}{l_0}$, the Kolmogorov refractive index spectrum is defined as

$$
\Phi_n(\kappa) = 0.033C_n^2\kappa^{-11/3}\,. \tag{4}
$$

where κ is defined as the scalar spatial frequency (radians/meter), and
where L_0 is the outer scale of turbulence (meters) as apposed to l_0, which is the inner scale of turbulence (meters).
Von Kármán modified the Tatarskii spectrum to include the smaller wave number (e.g. $\kappa < 1/L_0$), and then Andrews [1] later refined the von Kármán spectrum to account for the wave numbers beyond the inertial subrange and for the minor "bump" that has been recorded in the historical data. This is an approximation and is known as the *modified atmospheric spectrum* defined by

$$
\Phi_n(\kappa) = 0.033C_n^2\left[1+1.802(\kappa/\kappa_l)-0.254(\kappa/\kappa_l)^{7/6}\right]\frac{\exp(-\kappa^2/\kappa_l^2)}{\left(\kappa^2+\kappa_0^2\right)^{11/6}}\,,\quad 0\le\kappa<\infty, \tag{5}
$$

where $\kappa_l = 3.3/l_0$, $\kappa_0 = 1/L_0$.

<u>Laser Propagation Analysis</u>

Much work has been done in the area of laser propagation through space, however, it has been mostly in short range aircraft-to-aircraft, aircraft-to-satellite, ground-to-aircraft or ground to low-earth-orbit (LOE) satellites. This is an analysis of some of the possible systems that could be incorporated in ground to Molniya orbits.
In all long range communications the transmission media offers the greatest signal attenuation to the total system. In wireless/fiberless systems this attenuation takes the form of the radiation spreading phenomena and the fading or resistance due to the inherent energy and dynamics of the media. For ground-to-Molniya satellites the range from the earth's surface is on the order of 35,000 to 45,000 kilometers which offers a great deal of the described attenuation and will be further defined later.

The propagation model used here is based on early work done by Rytov and later refined by Andrews and Phillips [1]. The optical wave model is the Gaussian beam wave defined by the field equation

$$
U_0(x,y,0) = a_0\exp\left[-\frac{x^2+y^2}{W_0^2}-\frac{ik}{2F_0}(x^2+y^2)\right], \tag{1}
$$

where a_0 is the on-axis field amplitude, W_0 is the beam's spot radius at the transmitter, F_0 is the phase front radius of curvature, and k is the wave number defined as $2\pi/\lambda$. The variables x and y define the radial distance from the optical axis of the beam.

A laser beam will exhibit natural spreading as it travels from the ground out to intercept a satellite in a LEO or HEO. If we were to consider just free space, e.g. no atmosphere or turbulence, the radius of the receiver spot size will be defined by [1]

$$W = W_0\sqrt{\Theta_0^2 + \Lambda_0^2}\,, \tag{6}$$

where: W_0 is the radius of the beam at the transmitter,

$\Theta_0 = 1 - \dfrac{z}{F_0}$ which is the curvature parameter of the beam at the transmitter, and

$\Lambda_0 = \dfrac{2z}{kW_0^2}$ Λ_0 which is the Fresnel ratio of the beam at the transmitter.

In order to evaluate the Gaussian-beam wave $I(\mathbf{r},L)$ at the range, L, and in terms of the wave's characteristics at the transmitter, $I_0(\mathbf{r},L)$, the first, second and forth moments of the wave perturbations are calculated as $E_1(0,0)$, $E_2(\mathbf{r}_1,\mathbf{r}_2)$ and $E_3(\mathbf{r}_1,\mathbf{r}_2)$ respectively, Ref. [1]. The vector, $\mathbf{r}$, represents the offset coordinate from the optical axis of the beam and will later be replace with α, the offset aiming angle. From these calculations the mean irradiance at the receiver is calculated as

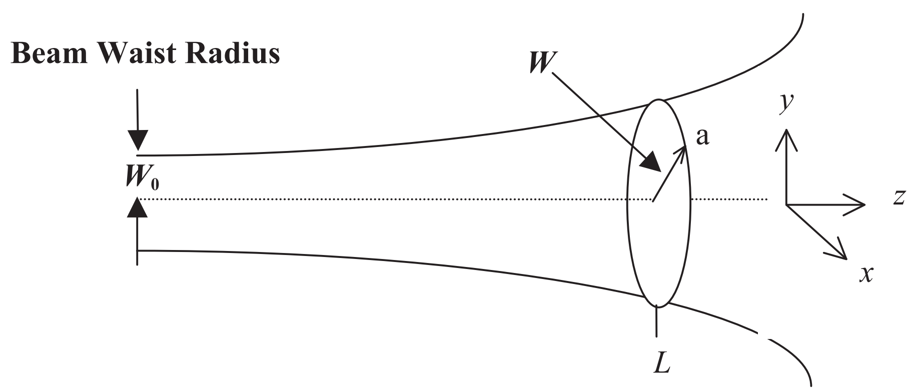

Figure 2 – Laser Beam Model

$$< I(\mathrm{r}, L) >= I0(\mathrm{r}, L)\exp\left[2E_1(0,0) + E_2(\mathrm{r},\mathrm{r})\right]. \tag{7}$$

The scintillation index is a value determined by comparing the scintillation at the optical axis of the beam to the scintillation at some known, radial distance, a, in the laser beam by $\sigma_I^2 = \dfrac{< I^2 >}{< I >^2} - 1$. By manipulating the moments the scintillation index for any position in the beam by

$$\sigma_I^2(\alpha, L) = 8.702k^{7/6}(H - h_0)^{5/6}\sec^{11/6}(\zeta)\left[\mu_3 + 1.667\frac{\mu_1\Lambda^{5/6}\alpha^2(H-h_0)^2\sec^2(\zeta)}{W_0^2\left(\Theta_0^2 + \Lambda_0^2\right)}\right] \tag{8}$$

where: $\alpha \le W/L$, $\alpha = \mathbf{r}/L$, $\mu_1 = \int_{h_0}^{H} C_n^2(h)\left(1 - \frac{h-h_0}{H-h_0}\right)^{5/3} dh$

$$\mu_3 = \mathrm{Re}\int_0^H C_n^2(h)\left\{\xi^{5/6}\left[\Lambda\xi + i\left(1-\overline{\Theta}\xi\right)\right]^{5/6} - \Lambda^{5/6}\xi^{5/3}\right\}dh$$

and where $\xi = 1 - \frac{h-h_0}{H-h_0}$ for uplink propagation and $\xi = \frac{h-h_0}{H-h_0}$ for downlink propagation.

The effective beam radius can then be calculated by

$$W_e = W\left(1 + 1.33\sigma_1^2\Lambda^{5/6}\right)^{1/2} \tag{9}$$

Orbit Characteristics and Tracking Solutions

Earth satellites are placed in a variety of orbit that can be basically classified as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Earth Orbit (GEO) and High Earth Orbit (HEO).
The LEO satellites travel in, basically, a circular orbit with an altitude from just above the atmosphere to an altitude of 2000 kilometers. A complete orbit can take from 90 minutes to a few hours. The International Space Station, Hubble and the Shuttle orbit in LEO paths. When communications is the main purpose, it is usually the case that a fleet of satellites is used so that the link can be maintained as one satellite flies out of sight while another one comes up over the horizon to pick up the transmission.
Midlevel Earth Orbit satellite altitudes orbit between the LEO and the GEO/HEO ranges with some overlap. Typically, the altitudes are from a few hundred to several thousand kilometers. The orbit times will vary from a few hours to around 12 hours. MEOs can be circular or elliptical depending on the specific requirements. The global positioning (GPS) satellites fall into this range.

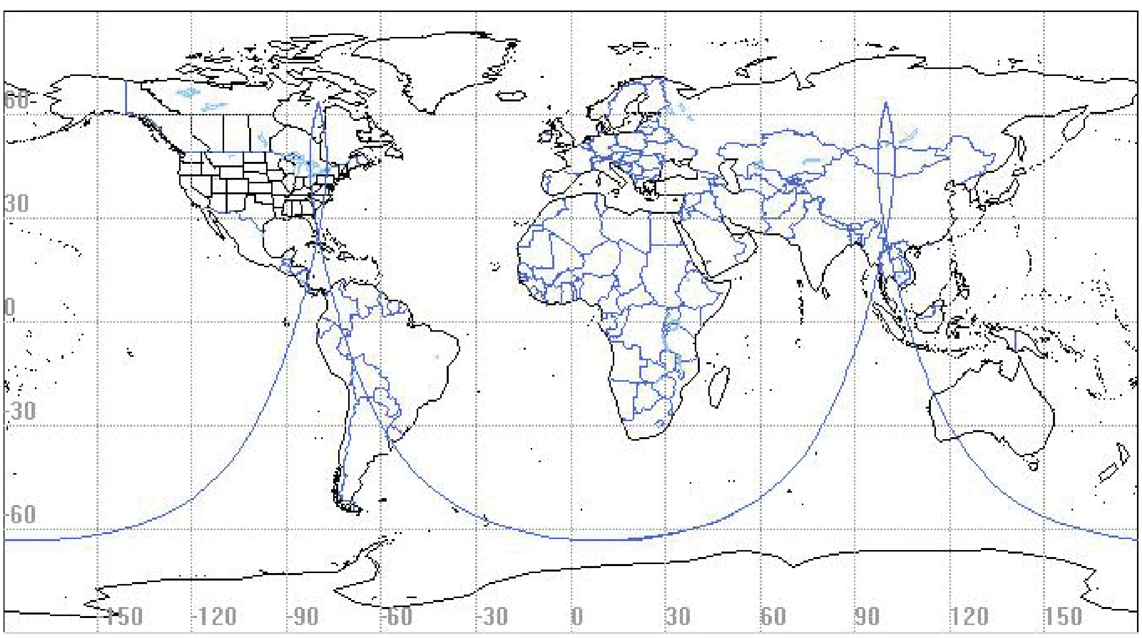

Figure 3 - Sample Molniya orbit ground track

Geostationary Earth orbits are very specialized in that they are oriented to align their plane of motion with the plane of the Earth's equator and their period of revolution is equal the rotation of the Earth.
The result of this geostationary placement is that the ground track of the satellite is stationary at a particular longitude, the latitude being fixed by definition at zero. Any ground station that can view the satellite from earth and is within the satellite's antenna footprint can have its antenna set to a fixed azimuth and elevation. No tracking hardware is required. The problem with using laser energy to communicate with satellites in geostationary orbits is that as the ground station is placed higher in latitude the signal path must travel through more turbulent atmosphere until the limit is reached between 75° - 81°, either north or south of the equator.

High Earth Orbits are elliptical in nature as shown if Figure 1. For a Mercator ground track See Figure 3. The Soviet Molniya communication satellites required a unique orbit solution that GEO (Geostationary Earth Orbit) orbits did not satisfy. That requirement was to provide line-of-site vectors for high latitudes that the majority of the Soviet Union occupied. The Molniya orbit will make two revolutions in 24 hours and the ground track of each satellite pass will repeat over the same latitude and longitude.
Defined by Kepler's third law, the length of time that the satellite is visible to the prescribed ground location, as it passes through apogee, is very long. As the satellite reaches its apogee it is also traveling at its slowest velocity in all vector directions relative to the Earth ground track. On the ground track of this particular orbit (Figure 3), this slowest point in space corresponds to the northern most point. Horizon-to-horizon communications can be achieved for well over 16 hours out of each day. However, for optical use only a much smaller span can be expected to give adequate results.

Single Laser Ground Station

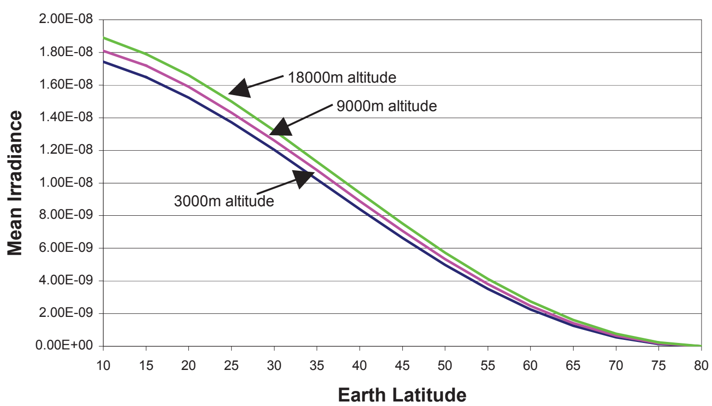

Figure 4 – Mean Irradiance

An example of an optical laser, with atmospheric effects taken into consideration, the beam diameter of a 4 cm laser at the altitude of 39,322,794 meters expands to 1,660 meters across. With a velocity of 1901 meters/second, the time that the satellite will be illuminated is approximately 0.873 seconds. This is not a very efficient use of the Molniya orbit. One way to compensate for this is to deliberately diverge or widen the beam so that it can capture more of the time around the point of apogee.

The mean irradiance of the laser as defined by [1]

$$Irr = \frac{W_0}{W_e} e^{\frac{-2r^2}{W_e^2}} \qquad (9)$$

Where W_e is the effective diameter and r is the orthogonal distance from the center axis of the beam to the point of observation. In this case we consider $r = 0$ since the concern is on the axis. Considering an ideal sky with no atmospheric obscurations, analysis has shown that varying the altitude has almost no effect on the mean irradiation. It can also be shown that as the latitude position of the ground station moves toward the poles, the increased length of turbulent atmosphere that must be transversed gradually degrades the mean irradiation of the laser signal to the point of extinguishment.

Communication Link Analysis

Laser energy interacts with its environment/media differently than does RF. Since the laser beam must travel through the atmosphere, turbulence becomes a predominant factor in the behavior of the energy as the receiver captures it. The following analysis will result in a figure of merit in the form of photo-electrons per second and graphical representations of the behavior of the beam.

This communications link analysis is based on the conventional technique of summing the power and antenna/amplifier gains and subtracting the various losses through the system.

$$E_T = e_T \cdot e_R \cdot P_T \cdot G_T \cdot G_R \cdot L_T \cdot L_p \cdot C_E \cdot L_R \tag{10}$$

Where:

E_T	Total optically generated photo-electrons
e_T	Transmitter antenna efficiency
e_R	Teceiver antenna efficiency
P_T	Transmitter peak power
G_T	Transmitter antenna gain
G_R	Receiver antenna gain
L_T	Transmitter loss
L_P	Propagation loss
C_E	Field intensity to photo-electron counts coefficient
L_R	Data rate loss

Since this is an impracticality it is necessary to count only the electrons generated based on the portion of the field that is seen by the receiving antenna. This is simply based on the ratio of the antenna area divided by total beam area which will establish a beam spread coefficient. Applying the coefficient will result in the actual predicted electrons-per-bit generated by the receiver. Figure 5 provides a quick insight into the required laser transmitter power requirements in order to generate greater than 30 counts from the satellites optical receiver. Based on a Pulse Position Modulation (PPM) with M-ary positions it can be seen that with an M of 8 the minimum average power required for a photo-electron count-per-bit rate minimum of 30 is 9.55 watts.

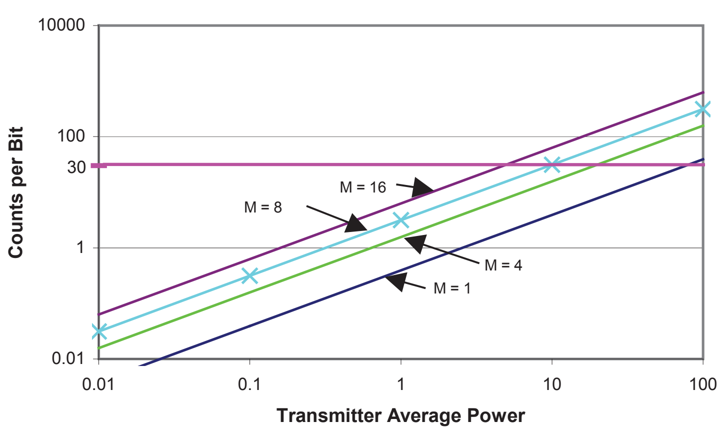

Figure 5 – Counts per Bit/Pulse

Discussion

The original goal of this investigation was to develop a laser to satellite communications scheme for ground locations in high latitudes that requires a minimum ground based tracking system. It is well established that geostationary orbits are the ideal for most RF ground stations that have fixed antennas. However, for the optical spectrum, these orbits are only suitable for ground locations in the tropic zones

around the equator. High latitudes are gradually precluded from using geostationary orbits due to energy absorption and the increasing path length of turbulent atmosphere that must be passed through. As stated in the introduction, the Russian developed Molniya orbit offers a viable solution for the higher latitude ground stations. The Molniya orbit allows these ground stations to have continual communication with small satellite constellation that can simulate the performance geostationary orbits. Although it is an ideal alternate solution for non-tracking RF ground stations, it still poses some challenges for laser terminals.
The investigation began with defining the atmospheric characteristics that will interfere with the use of a laser beam that would be used to communicate with a satellite traveling in a Molniya orbit around the Earth. A thorough definition of the laser beam and how it is affected by the random turbulence of the atmosphere was performed in a previous section. The original concept was to deliberately diverge the laser beam to the extent that the time that it illuminates the satellite, as it passes through apogee, was as much as 4 hours. If this could be accomplished then a modest constellation of only 3 satellites could sustain a continuous 24-hour communications link. The analysis showed, for a moderately high-powered laser and the ground station was located directly on the ground track of the Molniya orbit, that the turbulence was not the limiting factor. The link analysis disclosed that the limiting factor, in this configuration, was the power loss due to the divergence of the beam. The widely used measurement for the laser communications link is the electrons-per-pulse generated by the photon detector in response to reception of a laser pulse. Given a 10 watt average power laser, the output for a detector in this divergent state is 5.69E-07 electrons-per-pulse. We will take 30 photo-electrons per pulse as the minimum as suggested by Gagliardi [4]. Given that the resultant photo-electrons-per-pulse for the divergent beam scheme falls seven magnitudes below this minimum obviates the failure to adequately support a link.

The next tact was to assume an assembly of fixed laser emitters whose beams, at satellite altitudes, would form a continuous illumination across the required orbit path. Non-diverged lasers would require an enormous quantity of emitters. By deliberately diverging the laser beams to an optimal diameter this number can be greatly reduced but still not to a practical level. This optimization is simply accomplished by starting with a required electrons-per-pulse and working the mathematics backwards. Further reduction in numbers can be accomplished by configuring only the required lasers that will actually track a specific orbit path. The beamwidths of the lasers are optimized for maximum divergence resulting in the fewest number of emitters.

The number of emitters required for this configuration still remains high and may prove to be financially less attractive than full satellite tracking. Therefore, it would be interesting to know what tracking rates are required for the various orbit paths. Figure 6 shows the comparisons between the differing orbit paths. The maximum tracking angle for a LEO satellite is just under 1 degree per second and therefore, the time for the ground station to track 30 degrees before to 30 degrees after zenith is 1 minute and 12.4 seconds. A 2,000 km, circular MEO satellite remains in the same 60 degree view for a little longer, 4 minutes and 33.4 seconds. Its maximum angular rate is approximately 0.2 degrees per second. Expectedly, the 10,000 km,

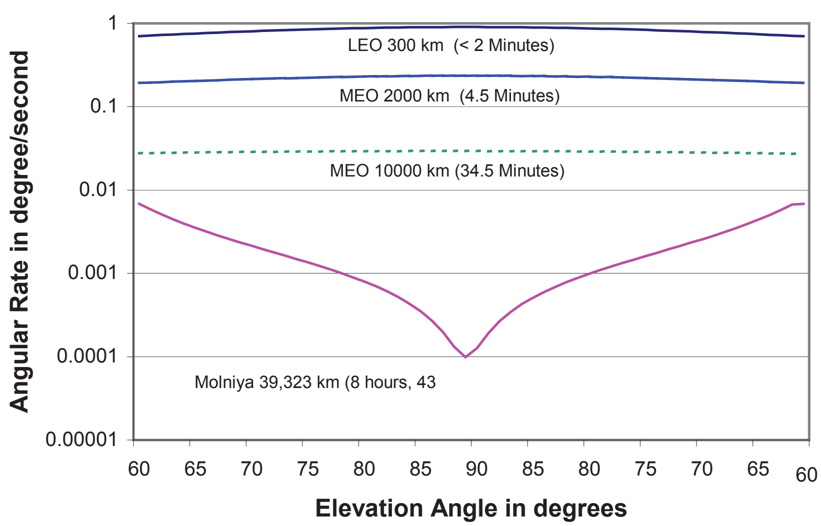

Figure 6 – Satellite Angular Velocity

circular MEO satellite is in the 60 degree view for 34 minutes and 27.3 seconds. The big jump comes in the Molniya orbit. Its tracking rates are reversed in that the peak of 0.008 degrees per second is at the entrance and exit of the 60 degree viewing area and that the lowest rate of 0.0001 degrees per second is at the orbit's zenith.

Although none of these tracking rates are stressing for today's technology the stability of maintaining the most accurate track remains with the Molniya orbit. The other consideration is the repeating characteristics of the different orbits. The Molniya orbit traces the same ground track from cycle to cycle. The same cannot be said of the other orbit paths. Several cycles of the orbit can go by before the satellite is physically in view and when it is it will rise and fall at a different azimuths and the path across the sky will be different each time. This would require an adaptive tracking system. The Molniya orbit, however, could be mechanically set to follow a single path that repeat exactly for each cycle.

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