Molniya System Alternatives for Geostationary Satellite Systems
with Application to 72-100 GHz Systems

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Abstract
We examine members of the Molniya satellite family for low cost and high communication performance. Eccentricities near 0.722 would allow high gain low cost ground antennas envisioned by the late W.T. Brandon. These simple single axis antennas would replace expensive AZ-EL trackers. A Brandon antenna is then applied to millimeter wave satellite communication in the 72-100 GHz region. We show attenuation results and a general equation which was derived from Barbaliscia’s key results. 80-90 GHz Molniya systems appear attractive for latitudes greater than 40 degrees at the 95% availability level.

1. Background

Geostationary satellite communication systems have clear and undeniable cost and simplicity advantages. With thousands of ground antennas in satellite television systems, the stationary ground antennas become a massive cost advantage over non-geo systems. However, the AIAA has recently reported that over 1000 satellites exist in geostationary orbit. More than 700 of these are uncontrolled. The environment may become physically crowded within the coming decade. The environment also may soon face electromagnetic crowding problems, with typical spacing at 2 degrees of orbital arc.

We noted at the Cleveland Ka Conference (1) that inclined, elliptic Molniya satellite systems have other kinds of advantages. The late W.T. (Bill) Brandon at MITRE Corp noted in the 1970s that the quasi stationary features of Molniya orbits offered interesting levels of ground antenna gain for stationary antennas. Stationary antennas were seen to allow moderate gain of 17-22 dB while communicating with the Molniya in the entire orbital arc from 30N to 63.4N. However, these satellites may have discouraged potential users because they apparently required expensive AZ-EL tracking ground antennas for high gain ground antennas. This became an important question when satellite TV transmission required ground antenna gains as 35-40 dB or greater.

We address the need for higher gain, at reasonable ground system cost, with a single axis of rotation for the ground antenna. The simplicity and low cost of single axis antennas has been demonstrated with back yard telescopes. Further, a careful choice of Molniya eccentricity will allow effective use of high gain single axis tracking ground antennas.

In the mid 60s, the Soviets recognized the Molniya satellite as an outstanding way to get good satellite coverage at high latitudes. They used an inclined elliptic satellite to get several hours of uninterrupted coverage at Moscow. Fig. 1-1a shows 1 hr snapshots of the 12 hour orbit. The Molniya orbits are even more useful for high latitude coverage than might be apparent from Fig. 1-1a. Since the ground station on the earth is rotating with the earth, the Molniya appears quasi-stationary for several hours. The three phased Molniya of Fig. 1-1b allow continuous satellite visibility. From the ground station’s perspective in a rotating coordinate system, the Molniya appear to rise directly North, as Fig. 1-1c.
Fig. 1-1c indicates that Molniya appears to be stationary for 4-6 hours at each apogee, and a very useful communication satellite for 8 hours. How could the system designer assure high elevation throughout the Northern Hemisphere for all time? One obvious solution would be to include two antipodal GEOS, as seen on Fig. 1-2. For lack of a better name, it might be called a MolniyaGEO system.
We examine sharp variations in the Molniya sub-satellite trace as a function of eccentricity with the aid of an accurate iterative solution of Kepler's Equation (2). These variations are especially sharp for the range 0.68 < e < 0.73. The sub-satellite trace (Fig. 1-3) for e=0.68 shows the halfwidth as 3.5 degrees Longitude, or a 7 degree total width.

Variations in Molniya eccentricity between 0.70 to 0.73 would allow (nearly) minimum E-W variations. These eccentricities would be favored for simple, high gain ground antennas with only one axis of rotation: e.g. to allow N-S tracking. These simple single axis trackers might be clock driven for low cost ground antenna systems. These simple high gain antennas may also approach the 35 dB gain level needed for satellite-to-ground TV transmission.

![Fig 1-3 Molniya Sub Satellite Traces for e= 0.64, 0.66, --,0.72; 6 Min.Intervals](image1)

A circular dish ground antenna could track single axis straight North-South with minimal pointing error near e=0.722 (Fig. 1-4). This would allow high gain (>40 dB) as Fig. 1-4.

![Fig. 1-4  RMS Tracking Error and Allowable Gain v. Eccentricity e](image2)
The comparison of Molniya eccentricities maybe seen more completely in 3D, as Fig. 1-5.

The 3D representation of two different eccentricities is represented as a *tetrahedron* for *e=0.64* and a *dodecahedron* for *e=0.722*. The latter eccentricity is seen to rise almost directly north, and a ground station in London could use an antenna with an East-West rotation axis: the simple modified Brandon antenna would swing directly north. It would deliver nearly minimum pointing error. However, the eccentricity 0.64 would imply very noticeable pointing error.
The minimum tracking error with optimum eccentricity (0.722) relates to a favorable ground tracking station at 0 East, as at London. The London station would see Molniya pass directly over its head, and the simple single axis would be a promising high gain candidate. Widely separated ground sites, as Boston (Fig. 1-6) may not be able to achieve this high gain with a simple single rotation axis. The Boston site would see the Molniya rise in a nearly straight line, but Fig. 1-6 gives more allowance for error angle with a 2.0 degree Beamwidth (circles on the Molniya path). It would correspond to a 36-39 dB gain.

The interesting Molniya system gains may be compared with typical gain for TV transmission as Table 1.

<table>
<thead>
<tr>
<th>Stationary Brandon</th>
<th>Single Rotation Brandon</th>
<th>Typical GEO for TV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain dB</td>
<td>dB</td>
<td>dB</td>
</tr>
<tr>
<td>20-24</td>
<td>36-39</td>
<td>38-42</td>
</tr>
</tbody>
</table>

The simple, single rotation axis Brandon antenna is suggested to be close to a level needed for TV transmission.

The Molniya advantages would also be manifested in higher available frequencies. We next show attenuation maps derived from Barbaliscia et al (3) and extended in 2003 (4) with the aid of an integrated gaseous attenuation model (5) to the 72-100 GHz region which would be useful for the Molniya orbits. The concise equation for zenith attenuation as a function of frequency, location, and probability is included (App.B). The equation is available in a more convenient form as a Mathematica program (6).

2. Millimeter Waves for Molniya Applications

The zenith attenuation of App. B can yield attenuation plots for a wide array of locations. Attenuation (at 95% availability) v. Frequency is shown for Miami (Mia), New York, and Oslo in Fig. 2-1a. Loss at constant antenna aperture is seen in Fig. 2-1b.
The zenith attenuation for 72-100 GHz is of interest here. The 80 GHz zenith attenuation may be found for 95% non rainy availability as Fig. 2-2. The 5 dB contour can be seen to lie on North Carolina.

Actual satellite elevation angles will raise the attenuation of Fig. 2-2. The Molniya satellites will allow much of the low attenuation advantages to remain for the Temperate Zone, but the higher attenuation will be noticeable in Fig. 2-3. An exhaustive worldwide search in location and time for 3 phased Molniya plus 2 geostationary satellites has been done (2). It yields a probability density function (pdf) as shown in Appendix A. It can be applied to Fig. 2-2 to yield the MolniyaGEO attenuation of Fig. 2-3.

The 5 dB contour of Fig 2-3 runs through Maine and Southern England.
The entire 80-90 GHz range may be especially attractive. Fig 2-4 shows zenith attenuation at 90 GHz. The 5 dB contour is indicated to pass through Washington DC.

The 5 dB contour for 90 GHz moves Northward from Washington to Northern Labrador for phased Molniya deployments of Fig. 2-5.
Conclusions
We have indicated that a careful choice of Molniya eccentricity near 0.722 would allow the complex, expensive AZ-EL ground antennas to be replaced with simple relatively inexpensive single-axis Brandon antennas. The Brandon antennas would be expected to offer attractively high data rate, in the neighborhood of that required for satellite-ground TV. The resultant system (3 Molniya satellites, 2 GEOS) with inexpensive ground antennas might be an attractive alternative to predominantly GEO systems with declining Real Estate.

The Brandon antennas would be further simplified with small 80-90 GHz (see attenuation of Sec 2) circular dishes.

Acknowledgements
Dr M.R.Dresp of the Mitre Corp had keen interest in the rates of change of Molniya Right Ascension and offered key insights. Dr. Paul K. Lee did definitive Ka band tests and was among the first to realize that Ka band communication could be reliable.

Selected References
Appendix A  Elevation Probability Density Function for MolniyaGEO  
Exhaustive computations for elevation angle for longitude, latitude, and time yields:
\[
P(x) = \frac{\left(-180.245 + 181.722 x - 0.776691 \text{LAT} + 0.279041 \text{LAT}^2 - 0.00526599 \text{LAT}^3 + 0.000023238 \text{LAT}^4\right)^2}{e^{\left(160.041 + 181.722 x - 0.776691 \text{LAT} + 0.279041 \text{LAT}^2 - 0.00526599 \text{LAT}^3 + 0.000023238 \text{LAT}^4\right)}}
\]

It can be seen as a function of latitude (LAT) as Fig A-1. Note high elevation groupings.

\[\text{Fig A-1 Elevation PDF for MolniyaGEO}\]

Appendix B  Zenith Attenuation as Function of LAT, LON, Frequency FG  
Non-rainy zenith attenuation can be expressed (4) as a function of frequency (fg), Latitude (LAT), Longitude (LON), and extremal probability level (PR). This shortened version runs well in Mathematica (6).

Zenith Attenuation (Gaseous and Cloud) =
\[
\text{dB} = \left[ a + b \left( \frac{\text{LAT}^2 - \text{LAT}}{\sqrt{2}} \right)^{2} \right] \text{dB} \quad \text{where} \quad \text{PR}=0.05 \text{ for 95% availability}
\]

\[\text{fg}= \text{frequency in GHz}; \quad 2 \text{ GHz} < \text{fg} < 100 \text{ GHz} \]

\[\text{LAT}= \text{Latitude, Deg. North}; \quad \text{LON} = \text{Longitude, Deg. East}; \quad a=0.0333667; \quad b=3.96; \quad c=0.7407407407\]

Where PR=0.05 for 95% availability