Small Satellite Constellations For EHF Polar Coverage

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ABSTRACT

Because atmospheric attenuation is greater for EHF frequencies than lower frequencies, it is necessary to design EHF satellite constellations so that the minimum elevation angles of the ground station antennas are larger than for satellite communication links using lower frequencies. The need for larger elevation angles reduces the coverage provided by geosynchronous equatorial satellites.

This paper examines how the size of the polar regions not receiving adequate EHF coverage varies with the number of equally spaced equatorial satellites. The suitabilities of 24 hour Tundra, 12 hour Molniya, and six hour circular orbits for providing the missing coverage are then examined.

The geographical location requirements for ground stations which link these satellites into global communication networks are analyzed. Three standard small satellite launch vehicles (SSLVs) can launch either three 12 hour Molniya satellites or six circular orbit satellites. While three Molniya satellites complete coverage of the northern hemisphere, six circular orbit satellites complete coverage of the entire globe.

Finally, ground station location is shown to be critical for networking Molniya constellations, while circular orbit constellations offer the use of existing defense communication system architecture EHF terminals.

INTRODUCTION

Military systems planners are finding the use of EHF satellites becoming increasingly essential to satisfy their projected requirements. Models of RF attenuation versus weather and geography show that atmospheric attenuation can be very severe for EHF signals. To provide acceptable communication channel availabilities, ground terminal antenna elevation angles of 20 degrees or larger are typically required.

This means that users in the polar regions can not communicate reliably with satellites in the equatorial plane using EHF signals. First, the next few pages define the size of the polar areas where the equatorial geosynchronous satellites do not provide reliable coverage; and then describe, evaluate, and compare satellite constellations which can provide adequate coverage of these polar regions.

DETERMINATION OF AREA WHERE COVERAGE IS REQUIRED

An equatorial geosynchronous satellite, when viewed by a ground station with the same longitude, can appear at an elevation angle of 20 degrees or higher only if the ground station is within the latitude band from 61.8 degrees south to 61.8 degrees north. When the ground station is not at the same longitude as the satellite, the width of the latitude coverage band is reduced. For 20 degree minimum elevation angle coverage, figure 1 shows the minimum width of the latitude coverage band as a function of the number of equally spaced satellites in the equatorial, geosynchronous constellation. Three such satellites spaced 120 degrees apart provide full coverage from 19.2 degrees south latitude to 19.2 degrees north. The equivalent latitude coverage values for four, five, and six satellites are 48.1, 54.3, and 57.0 degrees, respectively.

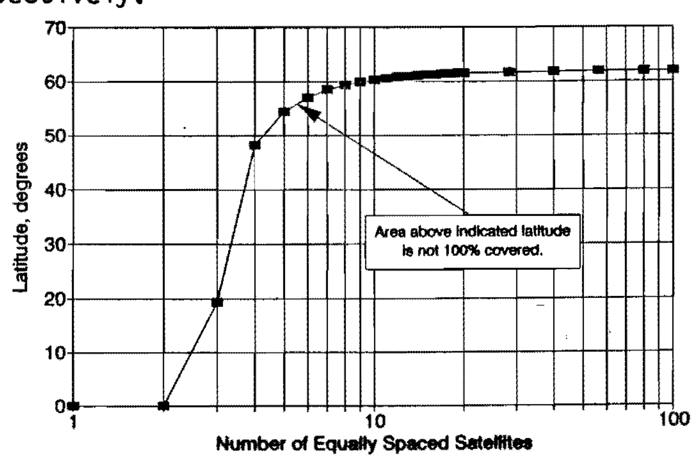


Figure 1. 100% Coverage Limited vs Number of Satellites for Geosynchronous Satellites and 20 deg Min Antenna Elevation

As figure 1 shows, the size of the areas which must be served by the polar coverage constellations depends upon how many satellites are available for equatorial coverage. The figures presented in this paper are intended to span large enough ranges to enable the reader to obtain approximate polar constellation solutions for any number of plausible equatorial satellites. However, to keep this paper concise and clear, only the four, five, and six geostationary satellite solutions are discussed. If the number of equally spaced equatorial satellites is four, five, or six then additional satellites must be used to provide complete coverage of the north polar cap area from 48.1, 54.3, or 57.0 degrees north, respectively, to the pole. Complete coverage of the southern polar region is also desirable but this coverage usually has a lower priority.

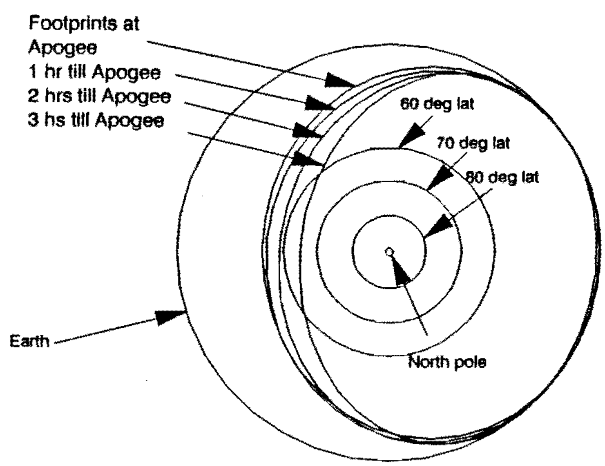
ELLIPTICAL ORBITS

When the objective is to maximize the coverage in one area at the expense of another, such as sacrificing Antarctic coverage in order to improve Arctic coverage, elliptical orbits can be useful. By using elliptical orbits with apogees over the target areas where the coverage is to be concentrated, the satellites are made to spend relatively more time over the target areas than they spend over other equivalent portions of their ground tracks. Because the earth is somewhat pear shaped, elliptical orbits about the earth tend to be unstable. Here, the term unstable means that the position of apogee tends to rotate within the orbital plane and the orbital plane also tends to rotate. The rate at which the apogee position changes varies as a function of the orbital plane inclination angle and is equal to zero for an inclination angle of approximately 63.4 degrees. This is why the Russian-developed 24-hour Tundra and 12-hour Molniya orbits use inclination angles of approximately 63.4 degrees. If any other inclination angle were used, the amount of fuel required for station keeping would be greatly increased. Thus, for economic reasons, elliptical orbits for long-term satellite communication constellations usage are limited to a single inclination angle, 63.4 degrees.

Having chosen 63.4 degrees for the inclination angle and selected the position of apogee to correspond with the most northern point on the ground track, four degrees of freedom remain: the orbital period, the orbital ellipticity, and the time and longitude at which apogee occurs. Usually it is desirable to select an orbital period which is equal to that of one revolution of the earth or a submultiple thereof, such as approximately 24, 12, or 6 hours, so that the satellite ground track returns to the precisely same earth locations at the end of each sidereal day (about 23 hours and 56 minutes). The selection of optimal ellipticity values leads to a discussion of Loopus constellations (Peter Dondl, "Loopus Opens a New Dimension in Satellite Communications", International Journal of Satellite Communications, Volume 2, pp 241-250, 1984). Since such a discussion is clearly beyond the scope of this paper, two representative elliptical orbits were selected, which have already been optimized for typical communications applications: the 24 hour Tundra orbit, and 12 hour Molniya orbit.

24 HOUR TUNDRA CONSTELLATIONS

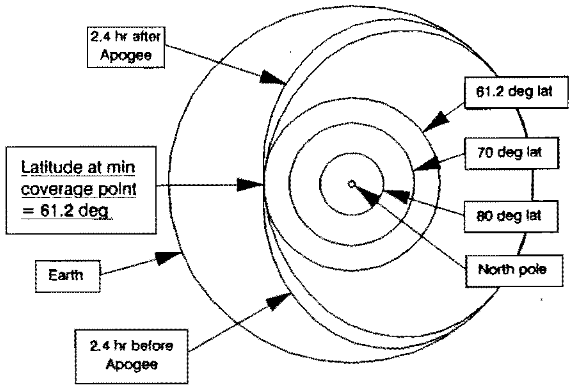
Figure 2 illustrates the 20 degree elevation angle coverage areas (footprints) of a Tundra satellite for zero, one, two, and three hours from apogee as they would appear when looking down at the north pole of the earth. Notice that the satellite footprint first encloses the 60 degree north latitude circle sometime between two and three hours prior to apogee. The footprint continues to enclose that latitude line until an equal time after apogee.



46,300 Km Apogee x 25,300 Km Perigee, 63.4 deg Inclination Orbit

Figure 2. Polar View of 24 Hour Tundra Satellite Footprints for 20 deg Min Antenna Elevation

Figure 3 shows the footprints at 2.4 hours before and after apogee. For the latitudes selected (above 20 degrees), the area which is inside of both of these footprints corresponds with the polar coverage area that can be obtained using five Tundra satellites sharing the same ground track and equally spaced in time.

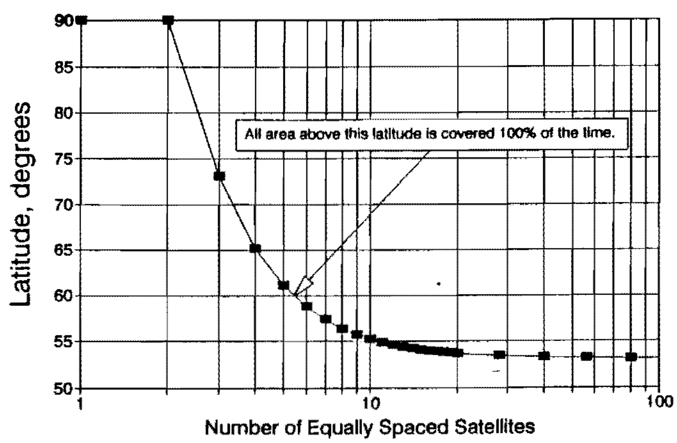


46,300 Km apogee x 25,300 Km perigee, 63.4 deg Inclination Orbits with the Same Ground Track

Figure 3. Polar Coverage at 20 deg Elevation for Five Satellite Tundra Constellation

Notice that both footprints enclose the 61.2 degree north latitude circle; therefore, the conclusion is that a constellation of five Tundra satellites can provide continuous coverage for the polar area at and above 61.2 degrees north latitude.

The points plotted in figure 4 were obtained by performing calculations equivalent to the graphical solution shown in figure 3 for various numbers of satellites.



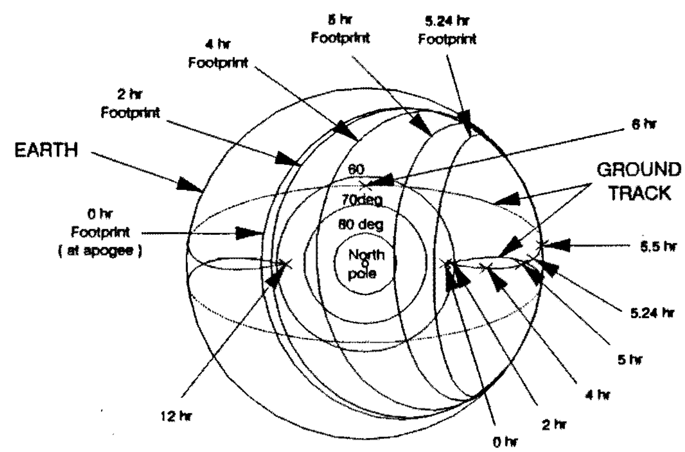
20 deg Min Elevation, 25,000 Nmi Apogee, 13,680 Nmi Perigee, 63.4 deg Inc

Figure 4. Polar Cap Coverage using Tundra Satellites on a Single Ground Track

The assumption that all of the satellites are equally spaced on the same ground track is implicit in these calculations. These solutions indicate that to obtain coverage down to 57.0 latitude as needed when using six geosynchronous equatorial satellites, eight Tundra satellites would be needed if they were equally spaced on a single ground track. Tundra satellites on a single ground track are not a practical solution for the six geosynchronous satellite 57.0 degree requirement and not even a possible solution for the four geosynchronous satellite 48.1 degree requirement. Better solutions can be obtained by using less satellites per ground track and more ground tracks; however, these options were not pursued because the 12 hour Molniya orbits considered below yielded less costly results.

12 HOUR MOLNIYA CONSTELLATIONS

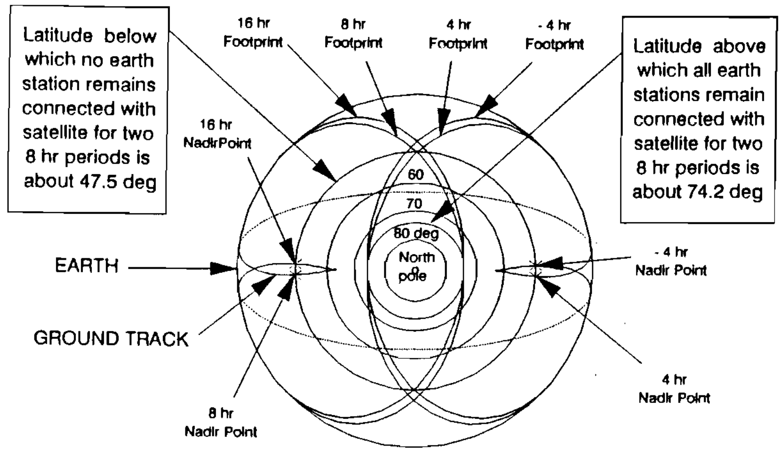
Figure 5 shows the ground track and several footprints of a 12 hour Molniya orbit on the Earth as seen looking down at the north pole. The two points 180 degrees apart on the ground track labeled "0 hr" and "12 hr" are the two apogee locations. Notice that the footprint size shrinks significantly as the satellite moves away from apogee.



39,900 Km Apogee x 500 Km Perigee, 63.4 deg Inclination Orbit

Figure 5. Footprints of a 12 Hour Molniya Satellite for a 20 deg Min Elevation Angle

For the region of interest (latitudes greater than 20 degrees), as the satellite moves away from apogee each footprint boundary is enclosed within all of the previous boundaries. Therefore, the area covered continuously from four hours before apogee until four hours after apogee can be determined by superimposing the footprints for these two times as shown in figure 6.



39,900 Km Apogee x 500 Km Perigee, 63.4 deg Inclination Orbit

Figure 6. Eight-Hour-View-Time Molniya Footprints for Min Elevation = 20 deg

The area enclosed by both of these circles (called the intersection in set theory notation) will be called the primary eight-hour-view-time coverage area. The equivalent area obtained by taking the intersection of the eight and 16 hour footprints will be called the secondary eight-hour-view-time coverage area. These eight-hour-time-in-view coverage areas represent the coverage which can be obtained using three 12 hour Molniya satellites spaced eight hours apart on a single ground track.

Constellations using elliptical orbits do not usually employ cross-links between satellites. The fact that elliptical orbit satellites sharing the same ground track move in widely separated orbital planes means that the distances and angles between the satellites can vary over such large ranges that implementation of cross-link antennas and transceivers becomes expensive.

In the absence of satellite to satellite cross-links, an isolated user needing to link into a global network must relay messages through a network connected terminal in the same footprint. If only one network connected terminal is available for relaying messages and it is in the primary eight-hour-view-time coverage area but not in the secondary area then, as shown in figure 6, only latitudes down to 74.2 degrees are totally covered.

If the network connected relay terminal is in the intersection of the two coverage areas, then the polar coverage extends down to 47.5 degrees latitude.

As shown in figure 7, the equivalent coverage latitude values for a Molniya constellation with four satellites six hours apart on the same ground circle are 63.6 and 37.4 degrees.

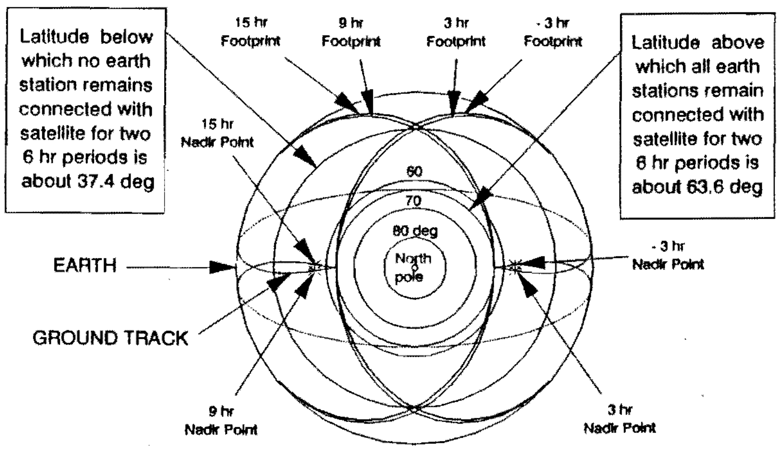


Figure 7. Six-Hour-View-Time Molniya Footprints for Min Elevation = 20 deg

EVALUATION OF MOLNIYA AND TUNDRA CONSTELLATION

As shown by figures 6 and 7, if the global connectivity provided by a network connected relay terminal (or terminals) in the primary coverage area is augmented by providing similar connectivity for the secondary coverage area, the size of the polar coverage cap is greatly increased.

A plot of the polar cap coverage latitudes for these two cases versus the number of equally spaced satellites on the same ground track is presented in figure 8.

The equivalent coverage for the Tundra satellites is shown on the same graph to facilitate comparisons. If three satellites are used and no network connected relay terminal is available in the Molniya secondary coverage area, then the Tundra constellation produces a slightly larger coverage cap (coverage down to about 73.1 rather than 74.2 degrees).

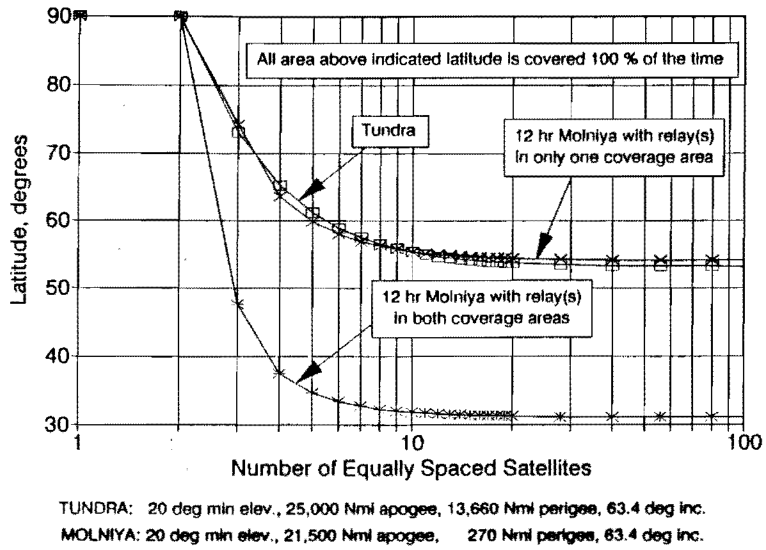


Figure 8. Polar Cap Coverage using Elliptical Orbits with Satellites on a Single Ground Track

In all other practical cases (less than 10 satellites per ground track) the Molniya constellation provides a larger polar coverage cap. When network connected relay terminals are available in both coverage areas of the 12 hour Molniya constellation, the Molniya polar coverage caps are significantly larger than Tundra coverage caps in all cases.

If only one relay terminal is used for connecting the Molniya constellation users to the global network, the location of that station has a critical effect on the size of the polar coverage cap. If this relay terminal is inside both coverage areas, it will enable the constellation to provide the larger polar cap coverage area indicated by the lower Molniya coverage line in figure 8. If the single relay station is inside only one of the coverage areas, only users in that area will be globally connected. Therefore, when only one of the coverage areas is globally connected the lowest latitude totally covered will be that indicated by the higher Molniya latitude coverage line in figure 8. Relay stations at or above the latitude indicated by the higher Molniya latitude coverage line in figure 8 are clearly inside both coverage areas. Terminals at or below the latitudes indicated by the lower latitude line in figure 8 can not be in both coverage areas.

An application of the general statements in the above paragraph to the three satellite 12 hour Molniya constellation with a single network connected relay terminal indicates that, if the relay terminal latitude is less than 47.5 degrees, the lowest latitude completely covered will be about 74.2 degrees. Conversely, if the relay terminal latitude is greater than 72.4 degrees it will be inside of both coverage regions so that the polar cap will be totally covered down to 47.5 degrees latitude. Whether a single relay station between 47.5 and 74.2 degrees latitude will support polar cap coverage down to the lower or the higher of these two latitudes depends upon the longitude of the relay station relative to that of the Molniya orbit ground track.

Circular orbit constellations will be discussed before stating further comparisons so that the final conclusions can be presented in a single location.

CIRCULAR ORBIT CONSTELLATIONS

If circular orbits are used, the inclination angles of the constellation orbits are no longer restricted to 63.4 degrees. As stated above, unless the inclination angle of an orbit is approximately equal to 63.4 degrees the non-spheroidal shape of the Earth causes the position of apogee to rotate in the orbital plane; however, for circular orbits this is not a significant problem because the apogee and perigee altitudes are essentially identical. It is also true that satellite orbital planes with inclination angles other than zero degrees tend to rotate about the spin axis of the earth. However, if all of the orbits in the constellation are inclined by the same amount, then they all tend to rotate at the same rate about the same axis. Thus, constellations made up of orbits which are all inclined by the same amount tend to rotate as a single solid object would; therefore, for most purposes, this rotation does not degrade the performance of the constellation.

Having shown that one is free to choose any inclination angle when using a circular orbit, the inclination angle is set to 90 degrees so that the satellites pass directly over the poles maximizing the polar coverage per satellite.

The altitude of the satellites was chosen to be as high as practical while still permitting two satellites to be launched using only one SSLV.

After making tradeoffs between altitude and payload capability a 5600 Nmi circular orbit with a 90 degree inclination angle was selected. The weight estimates include shielding for the heavy

Van Allen belt radiation encountered in portions of this orbit. The size of the polar coverage regions for constellations with various numbers of equally spaced satellites in the same plane with six hour (5600 Nmi high) circular orbits have been computed and the results are plotted in figure 9. Such constellations with four, five, six, or seven equally spaced satellites can provide polar cap coverage down to 68.0, 54.1, 49.2, or 46.7 degrees, respectively.

Unlike the elliptical orbit constellations, the circular orbit constellations cover both the Arctic and the Antarctic polar caps. In some cases, such as the recent Falkland Island crisis, this difference can be significant.

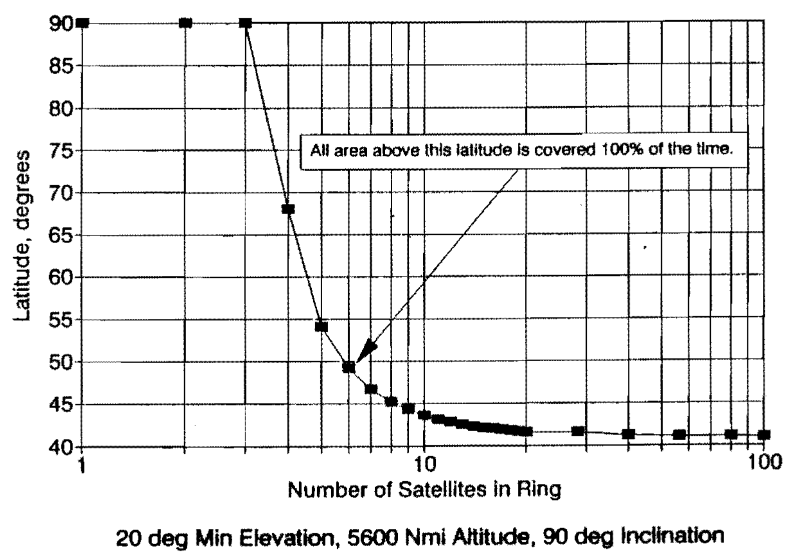


Figure 9. Polar Cap Coverage using a Circular Orbit

The weight budget for this constellation includes satellite to satellite cross-links so that messages from the polar areas can be relayed back to network connected terminals in more hospitable climates. When estimating the acquisition costs and operational costs of a satellite constellation and ground terminals it is important to determine whether the required network connected ground terminals already exist or whether new terminals must be built and maintained. This question has already been addressed for a navy application. Figure 10 indicates that the navy already has enough NAVCAM terminals to assure that at least one existing terminal will be in the coverage band of a 5600 Nmi circular polar orbit, six satellite, polar coverage constellation for the entire 24 hour period during which the earth rotates 360 degrees with respect to the orbital plane.

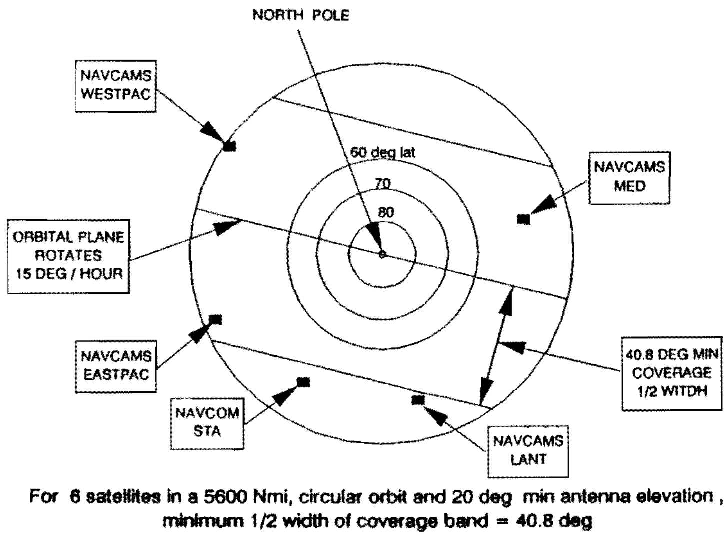


Figure 10. Polar Orbit Linkages with NAVCAM Terminals

The reason that six satellites were used rather than the minimum required number, five, is that each SSLV carries two satellites. In order to demonstrate that the coverage from this constellation is concentrated in the polar regions while still being significant in the equatorial regions, the average number of satellites in view has been computed as a function of the latitude and minimum antenna elevation angle and the results are plotted in figure 11.

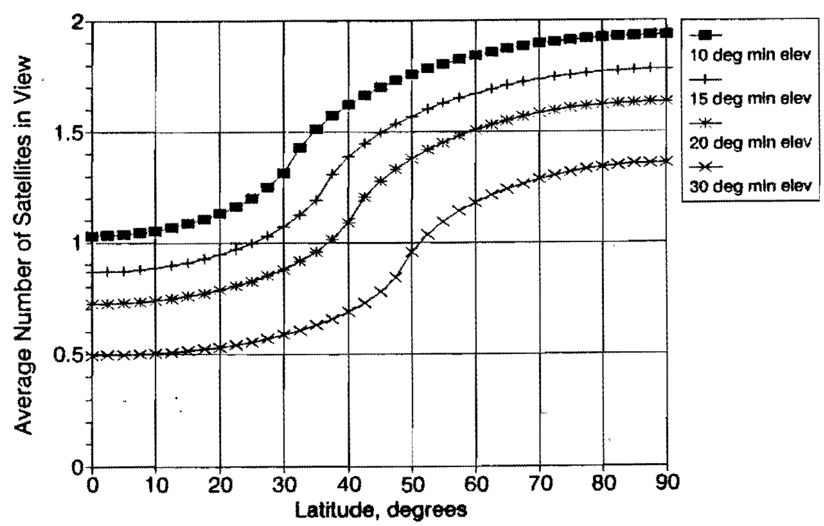


Figure 11. Average Coverage vs Lat & Min Elevation 1 × 6 Sats, Alt 5600 Nmi, Inc 90 deg

COMPARISONS AND CONCLUSIONS

Using the results presented above it is possible to determine how many satellites are needed to cover the polar cap areas for various numbers of equally spaced equatorial geosynchronous satellites. The results are summarized in table I. Notice that none of the constellations discussed here will provide adequate coverage of the areas missed by the equatorial geosynchronous satellites unless at least four equatorial satellites are used.

Table I

Polar Coverage Options

Number of Geosynchronous Equatorial satellites Highest latitude Fully covered	3 19.2	4 48.1	5 54.3	6 57.0
24 hour Tundra, 1 track # Satellites needed Latitude covered	no solution	no solution	14 54.2	8 56.4
12 hour Molniya, 1 track Using single coverage area # Satellites needed Latitude covered	no solution	no solution	not practical	7 56.8
12 hour Molniya, 1 track Using both coverage areas # Satellites needed Latitude covered	no solution	3 47.5	3 47.5	3 47.5
5600 Nmi Circular Orbit Inclination = 90 degrees # Satellites needed Latitude covered	No solution	7 46.7	5 54.1	5 54.1

Among all of the options, the three satellite, single ground track, 12 hour Molniya constellation requires the fewest satellites. One of the issues to be resolved before settling on the three Molniya satellite solution is the location and cost of the network connected ground terminals. Another is the potential cost of implementing spacecraft antennas, receivers, and transmitters which are capable of operating close to the theoretical efficiency limits under the widely varying range, pointing angle, and beam width requirements shown in figure 12. Adding a forth satellite to the constellation could reduce the required operating ranges by reducing the individual satellite viewtimes from eight hours to six hours; however, a thorough cost tradeoff should be made before choosing such an option.

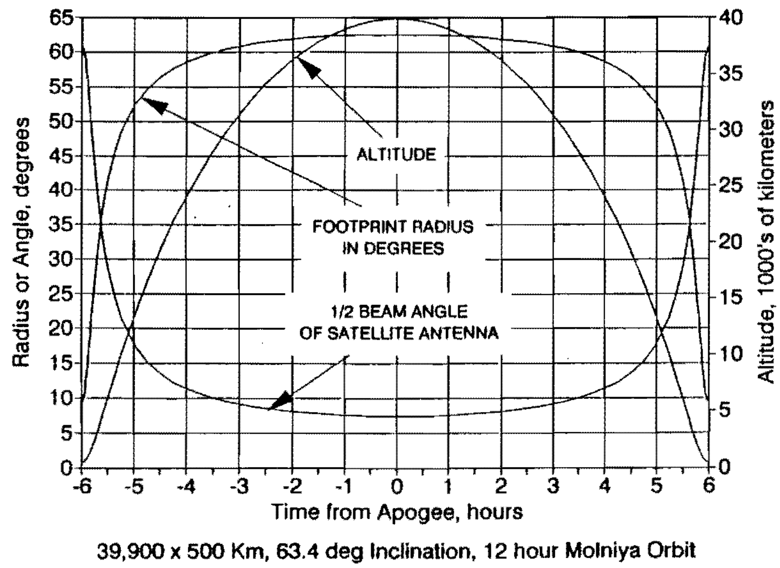


Figure 12. Altitude and Angles versus Time for 12 Hour Molniya Orbit

Since the 5600 Nmi, 90 degree inclination, circular orbit satellites are launched two at a time on one SSLV, six of these satellites could be launched using the same three SSLVs that would have been needed to launch the three Molniya satellites. Thus, if more than four equatorial geosynchronous satellites are used, the circular orbit constellation would require no more SSLVs than the 12 hour Molniya constellation. If coverage of the southern hemisphere becomes an important consideration, the circular orbit has a decided advantage because the 12 hour Molniya constellation with apogees in the northern hemisphere does not provide coverage in the southern hemisphere.

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Biography

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Prior to joining E-Systems, Dr. Acker was a Corporate Shared Internal Consultant and Lead Systems Engineer for Honeywell. He was directly responsible for system design, simulation and component development for analog and digital signal processing. He has over 20 patents in communications and related areas.