The NUONCE Engine for LEO Networks

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ABSTRACT

Typical LEO networks usc constellations which provide a uniform coverage. However, the demand for telecom service is dynamic and unevenly distributed around the world. We examine a more efficient and cost effective design by matching the satellite coverage with the cyclical demand for service around the world. Our approach is to usc a non-uniform satellite distribution for the network. We have named this constellation design NUONCE for Non-uniform Optimal Network Communications Engine.

INTRODUCTION

On July 26, 1963, the Syncom satellite was successfully launched into orbit and became the world's first geosynchronous communications satellite. This joint venture of the Hughes Aircraft Co. with NASA revolutionized the telecommunications world. These satellites have affected every aspect of our lives and changed the way we live. Today, a ncw revolution in the world of satellite communications is in the making: the Low Earth Orbit (LEO) satellite communications networks. The April 18, 1994 issue of Space News [1] lists no less than 12 companies with proposed global networks. Teledesic Corp. leads the pack with a network of nearly 1000 satellites. This April, Orbital Communications Corp. is scheduled to launch the first two of its 36 Orbcomm data communications satellites.

Typical LEO networks usc uniformly distributed constellations to provide uniform coverage. These networks tend to use circular orbits with almost identical altitudes, evenly spaced in the orbit planes. The resulting constellation is usually highly symmetrical. However, the demand for telecommunications service is dynamic and highly non-uniform. This is because the users are unevenly distributed on the continents which cover only a quarter of the earth. Furthermore, there is a bimodal diurnal cycle in the demand for services duc to the business day. This suggests that perhaps a dynamic non-uniformly distributed network is more efficient.

We have named this constellation design NUONCE, the Non-Uniform Optimal Network Communications Engine. Such a network would require fewer satellites and may reduce the capital overlay required to the benefit of both industry and consumers alike. The NUONCE constellation may also provide a good phased implementation strategy. Since the network is non-uniform to begin with, the routing, traffic management and operations are designed to function accordingly. The early sparse phase could target certain limited markets. As the demand increases, additional satellites could be added to the network. This enables an adaptive and evolving network with greater flexibility than a fixed uniform constellation both in the implementation and the resource management. Of course, this would demand a more carefully thought out telecom design that would permit migration from one configuration to another.

GOAL

Our goal in this paper is to consider some orbital design strategies to help the satcom system designer to come up with a non-uniform constellation. Specifically, wc want to find constellations which will spend most of the time in the day side where the demand for telecom service is highest.

CONVENTIONS AND COORDINATES

Frequently, the right picture will suggest the solution to a seemingly difficult geometric problem. In this case, the rigid picture is provided through the use of rotating coordinate systems. Fig. 1 below shows the equatorial plane of the earth as viewed from above the north pole. Assume at time O the sun is in the direction of the y-axis at the top of the figure. in earth-centered inertial coordinates, the sun moves roughly 10 per day counter-clockwise. Thus 1 day after time 0, the sun will no longer point in the y-direction but will be in roughly 10 to the left of the y-axis. However, if we let our coordinate systcm rotate counter-clockwise to match the apparent motion of the sun, wc then have the sun always fixed in the y-direction. Wc will adopt this rotating coordinate systcm in the following discussion. The reason this coordinate. system is useful for our problem is because wc want to find orbits which linger on the sun-sick. as stated in the goal above..

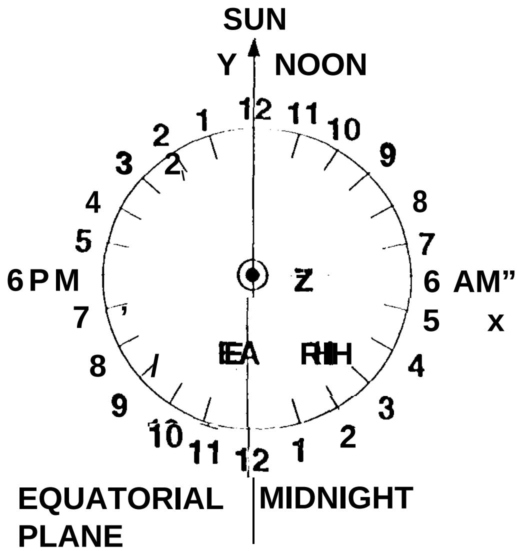

Figure 1. Rotating Coordinate System

We now define some conventions to be adopted for the discussion in this paper. Note in Figure 1, we have marked the different longitudes with their local times. We define the "day side" to be 6 AM to 6 PM going counter clockwise. This is the top half of Figure. 1; the bottom half is the "night side".

To simplify the discussion, unless otherwise noted, we assume the orbit of earth is circular and that the equator coincides with the ecliptic. However, we do include the first order effects of the earth's equatorial bulge which cannot be ignored for LEOs. For this discussion, we define. a LEO to be an orbit with altitude under 2000 km, a MEO (Medium Earth Orbit) to be an orbit with altitude under 16763 km (6 hour period), a HEO (Highly Elliptical Orbit) to be an orbit with eccentricity greater than 0.1.

CIRCULAR VS. ELLIPTICAL ORBITS

In order to quantify the performance of an orbit, we define a metric called the Day Side Fraction. This fraction is the ratio of the amount of time a satellite spends in the. day side of an orbit divided by the orbit period. For example, the day side fraction of circular orbits is 0.5.

Let us look at a typical circular LEO at 200 km altitude and 85° inclination with a period of about 1.5 hours. Figure 2 is a plot of 4 satellites clustered together in this orbit. But, clearly the cluster will spend just as much time in the day side as in the night side. So an uneven distribution of satellites in this orbit does not seem to help our cause. In fact, given a satellite in any circular LEO about the earth, it will always spend equal time in both the day side and the night side.

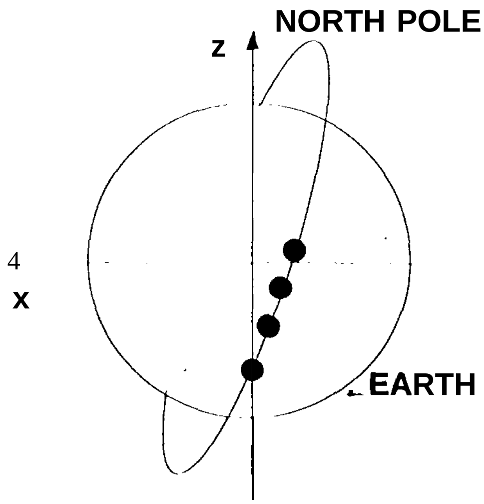

Figure 2. Four Satellite Cluster in a Circular LEO Orbit

This suggests using elliptical orbits. Figure 3 shows the fraction of time per orbit a satellite is in the day side as a function of orbit eccentricity. For this calculation, we assume the perigee is placed at the equator. Thus the apogee is also on the equator. Figure 4 shows what this means geometrically. For a given orbit plane and eccentricity, this orientation provides the greatest day side fraction for an orbit. For example, a Molniya orbit has e=0.75 which yields a day-side. fraction of 93%. This means it spends 93%, of each orbit on the day side. But, with a period of 12 hours, the Molniya orbit is a HEO. What about elliptical LEOs?

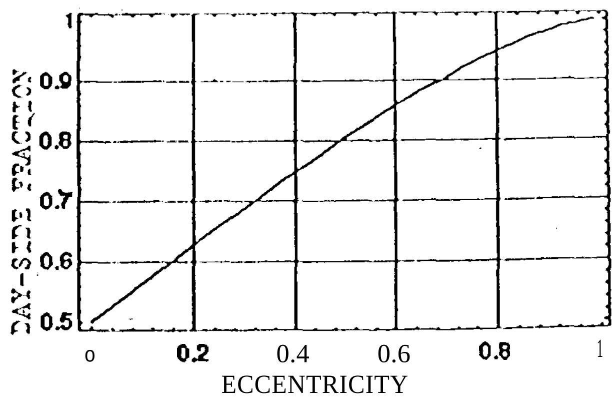

Figure 3. Day Side Fraction vs. Eccentricity

In the range we are. considering (altitude< 2000 km), what are the most eccentric elliptical orbits we can consider? Since the altitude is restricted to be less than 2000 km, this means the apogee must be less than 2000 km. The perigee can vary from 200 to 2000 km. Table 1. below lists a few of these orbits, their eccentricities, and day-side fraction.

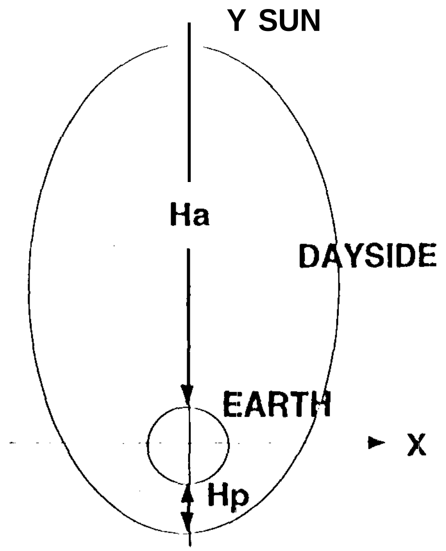

Figure 4. Geometry of Day Side Fraction

Hp/Ha (km)	Etc.	Fraction	Minutes
200/1000	0.0573	0.5364	3.5
30W1OOO	0.0498	0<5317	3.1
400/1000	0.0424	0.5270	2.7
450/1000	0.0387	0.5246	2.4
475/1 Ooo	0.0369	0.5235	2.3
500/1000	0.0351	0.5223	2.2
200/2000	0.1204	0.5764	8.2
300/2000	0.1129	0.5717	7.8
400/2000	0.1056	0.5671	7.3
450/2000	0.1019	0.5645	7.1
475/2000	0.1001	0.5636	7.0
500/2000	0.0983	0.5625	6.9

Table 1. The Day-Side Fraction of Selected LEOs

Hp/Ha are the perigee and apogee altitudes of the orbit. Ecc is the eccentricity of the orbit. Fraction is the Day-Sidc Fraction and the resulting extra time spent on the day side per orbit is the last column. Realistically, in order to avoid drag decay of the orbit, the perigee should be around 500 km. Thus the 500/2000 case is the most eccentric orbit to be used in a LEO. This provides a maximum of about 7 minutes of extra time on the day side for an orbit period of 108 minutes. If wc drop the apogee altitude to 1000 km, the 500/1 000 case yields a 2 minute advantage on the day side for an orbit period of 100 minutes. Thus elliptical orbits will increase the day-side portion of the orbit. Even a small savings of a fcw per cent is significant when the stakes arc high.

Unfortunately, this is not the entire story. The equatorial bulge of the earth introduces other challenges. The dominant term of the perturbation in the geopotential with coefficient J2 causes the orbit planes to precess about the poles. This is called "nodal precession" because the precession is defined by the motion of the orbit node where the satellite first crosses the equatorial plane into the northern celestial sphere. J2 also causes the line connecting tbc perigee and the apogee to rotate within the orbit plane about the orbit normal vector. This is called "apsidal rotation". We note that apsidal rotation dots not affect a circular orbit since it has no apogee or perigee.

TO first order, these. perturbations are governed by the orbit semi major axis, eccentricity, and inclination. For the LEO elliptical orbit at 85° inclination with 500 km perigee height and 2000 km apogee height, the nodal precession is -0.47°/day and the apsidal rotation is -2.60/day. For the same elliptical orbit at the lower inclination of 28.5°, the nodal precession is -4.8 '/day and the apsidal rotation is 7.8 '/day. Thus, for tbc 28.5° orbit, the apogee will have moved 180° in less than a month. So if it started in the day side, it will now be in the night side.

This can bc fixed by using orbit planes at the critical inclination of 363.43" where the rotation of the perigee is eliminated. However, there remains the precession of the node. At critical inclination, the nodal regression of the 500/1000 LEO elliptical orbit is still -2.40/day. In 150 days, the orbit plane will have precessed 360° around the equator. Thus we arc unable to force the orbit planes to rem ain in their time slot. Fortunately, sun-synchronous orbits (see next section) solve this problem.

Alternatively, we should mention that both the nodal precession and the apsidal rotation can be fixed by propulsive maneuvers. But this requires a lot of orbit maintenance which is expensive both in the fuel and operational costs. However, new technology using continuous low thrust and autonomous control may provide answers to these problems in the near future. But, for this discussion, wc do not consider this kind of technology although the orbit design strategy described in this paper is equally valid and compatible with the ncw technology.

SUN-SYNCHRONOUS ORBITS

Sun-synchronous orbits are those orbits whose nodal precession rates exactly match the orbital motion of the earth around the sun. The orbit plane maintains a near constant geometry with respect to the sun. Sun-syncronicity is determined by three orbit parameters: semimajor axis, inclination, and eccentricit y, and requires inclinations greater than 90°. Now each orbit still goes through the full 24 hours of time zones during onc revolution and it has the interesting property that it always passes the same latitude at the same local mean time. For example, we want an orbit over New York City (410 latitude) at 10 AM. Figure. 5 [2] below is a plot of the local mean time as a function of the satellite nadir latitude in an orbit centered on NYC at 10 AM. Note that the variation of the local mean time for this orbit is fairly narrow. From -50° to 50° latitude, the variation of the local mean time is just 1 hour. Figure 6 is a plot of the orbit over earth as viewed from the sun. This geometry will remain fairly constant over time.

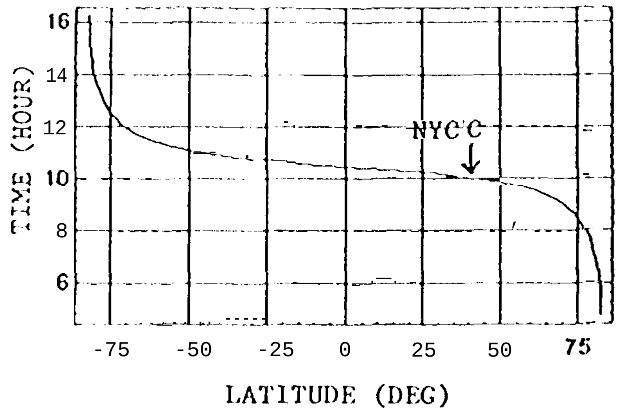

Figure 5. Local Mean Time of 10 AM Orbit Over NYC

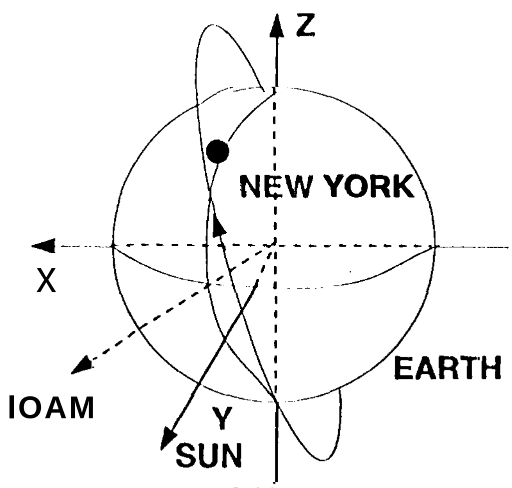

Figure 6. View of 10AM Orbit From the Sun

This suggests we can use sun-synchronous orbits to optimize the day side coverage as follows. Suppose we want to cover New York City and we expect the heaviest traffic over New York to be from 9AM to 3 PM. Let us start with a Walker constellation of circular orbits as an example of a uniformly distributed constellation and change it into a NUONCE constellation. The Walker design has all satellites at the same altitude and inclination [3] where the satellites are spaced evenly within each orbit plane and the planes are evenly spaced around the equator, The phasing of when the satellites cross the equator in adjacent planes is also the same for all orbit planes. The aim of the Walker constellation is for continuous global coverage. But, the aim of the NUONCE constellation is to maximize coverage of high demand regions over day time. For our satcom example, suppose a sun-synchronous Walker design requires an orbit plane every 15° (1 hour) apart with 6 satellites per orbit. This requires 12 planes with 72 satellites total. Figure 7 below is a schematic diagram of this design. The lines around the clock represent orbit planes with nodal crossings at the time indicated. For simplicity, the inclination is not represented.

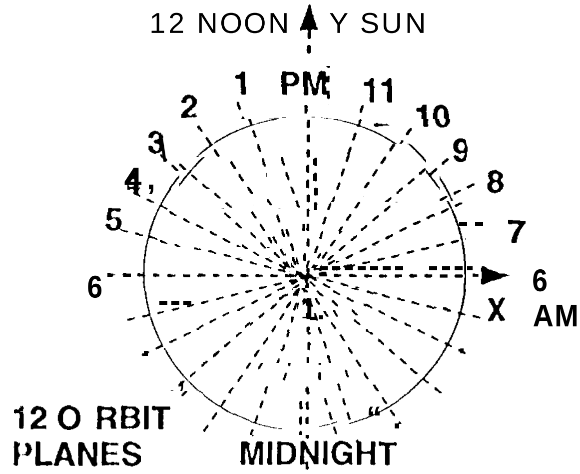

Figure 7. Diagram of Walker Constellation

Since the usage from 6AM to 9 AM and 3 PM to 6 PM will be low, perhaps just a single plane at 6PM with 4 satellites is sufficient to handle the traffic. Also, at 12 Noon, there will be less demand due to the lunch hour. So the 12 PM plane may be removed. The resulting constellation has 7 planes with 40 satellites total. Figure 8 below is a schematic diagram of this design. This shows a dramatic reduction of 32 satellites. Of course, this is just an example to illustrate the approach without the detail analysis verifying whether the real coverage demand has been met.

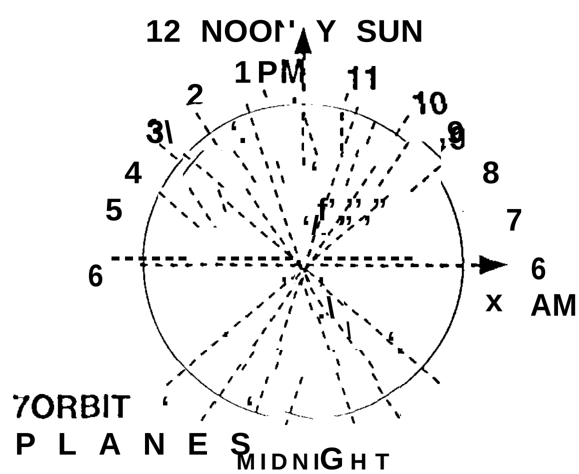

Figure 8. Diagram of NUONCE Constellation

NON-UNIFORM STRATEGY

Now that wc have discussed circular orbits, elliptical orbits, critically inclined orbits, and sun-synchronous orbits, wc can put the pieces together to formulate a non-uniform satcom orbit design strategy. Recall the aim for our NUONCE constellation is to optimize day-side coverage. Ibis can be achieved by using the following guidelines:

1. Usc sun-synchronous orbits (inc. > 90°) so that onc can control the local time passage at specific latitudes.

2. Concentrate the orbit planes with specific longitudes in time zones of highest usage demands.

3. Evenly space the satellites within each plane. In planes over regions and time z.ones of high demand, increase the number of satellites. In planes over regions and time zones of low demand, decrease the number of satellites.

4. Use elliptical orbits where possible. Place the apogee over the latitude of a region of high demand at the peak hours.

s. Usc critical inclination to control the apsidal rotation in elliptical orbits. Critically inclined sun-synchronous orbits exist only at the inclination of 116.57° (-63.430).

USING HEO

What about using elliptical orbits to take advantage of all the extra capacity wasted on the night side? For our 500/2000 km LEO elliptical orbit, the sun-synchronous inclination is 100.46° and the apsidal rotation rate is still a hefty -2.30/day. Thus, wc need to use critically inclined sun-synchronous orbits. But this would bring us out of the LEO realm since a circular sun-synchronous orbit has an altitude of 3438 km.

Suppose we want an elliptical orbit with 70% day side coverage per orbit. From Figure 3 we see that this requires an eccentricity of 0.32. A sun-synchronous orbit with this eccentricity at critical inclination will require a semimajor axis of 10441 km. This gives a perigee/apogee altitude. of 722 km/ 7404 km with a 3 hour period. The apogee is fixed by the critical inclination and the orbit plane follows the sun synchronously as designed. Clearly, this provides much better day-side coverage than a circular LEO if time is the only consideration. This is in fact like the HEO orbit selected by Ellipso as part of its constellation design.

CONCLUSION

The observations of this paper suggest that uniform circular LEO constellations arc not optimal for the day-side coverage. However, a non-uniform distribution which dots not usc sun-synchronous orbits will not provide good coverage of the day side due to the precession of the orbit plane and the rotation of the apogee. Similarly, although an elliptical orbit can increase the coverage on the day-side., its apogee must somehow be fixed on the day-side.

Using sun-synchronous orbits, the day-side coverage can be optimized by concentrating the orbit planes in the time zones with the heaviest traffic. This can be achieved with circular LEOs. By using critically inclined sun-synchronous HEOs, the day-side fraction of the coverage can be increased significantly to 70% or more.

This paper provides guidelines to assist in the orbit design process to ensure maximum coverage on the day side. More detailed analysis is required, but the NUONCE constellation concept clearly provides better coverage than a uniform constellation. These conclusions address only the geometric c.overage. issue and do not take into consideration other important issues such as the telecom design, spacecraft design, impact on operations, and launch cost which will impose. other constraints on the constellation design.

ACKNOWLEDGMENTS

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REFERENCES

[1] Space News, pp. 1, April 18, 1994.

[2] J. R. Wertz (cd.), "Spacecraft Attitude Determination and Control", D. Reidel Publishing Company, 1980, pp. 68-69.

[3] J. G. Walker, "Circular Orbit Patterns Providing Whole. Earth Coverage", Royal Aircraft Establishment Technical Report 70211, November 1970.