POPULATING THE ABYSS-INVESTIGATING MORE EFFICIENT ORBITS

-or-

"GETTING MORE MILES TO THE GALLON FOR YOUR (SPACE) VEHICLE"

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Abstract

Most satellites operating in orbit are spatially distributed in one of the following regions: LEO (below 600 nm and below), MEO (Molniya and GPS), and GEO (synchronous circular). Other than Molniya and a few similar systems, little use has been made of either elliptic orbits or the 'middle-ground' orbits lying between 600 nm and synchronous altitude. This paper explores the potential for exploiting these less populated regions and demonstrates that analyzing system optimization parametrically may in fact, also dictate an increasing interest in this new territory. A non-dimensional coverage parameter is presented which indicates that the 'efficiency' of an orbit may indeed be optimized for altitudes between 1000 to 10,000 nm. This factor usually appears to peak at slightly under 2000 nm. Elliptical orbits (requiring less booster energy than circular orbits of like period) can provide better coverage for specific geographical areas of interest by properly locating the apogee and by using repeating ground tracks. Although radiation has been a significant factor, a judicious choice of orbits coupled with advanced technologies to harden electronic circuits and solar cells may alleviate radiation effects. The increasing use of multi-satellite arrays, or constellations, demands that system costs be minimized; an obvious approach is to design for the minimum number of satellites (and boosters) required to satisfy the requirements.

I. Background

The field of satellite constellation design has evolved since the first Russian Sputnik I satellite was launched October 4, 1957, and has continued to mature to the present time. The low earth orbit (LEO) orbital space, generally 600 nm or less in circular or near-circular orbits, has been extensively used for research, earth sensing, and manned missions. A major advance was achieved with the launch of the first geostationary (GEO) satellite, SYNCOM 2, on July 26, 1963, which ushered in a new era in communications satellite technology. The Russians, meanwhile, selected the Molniya architecture of 12 hour elliptic comsats, which gave them more effective coverage of the high latitude regions of the USSR. The above rather distinct three regions of orbital space have all been extensively exploited (and populated) almost to the exclusion of other options. Figure 1, a plot of over 1600 satellites, shows their grouping in the orbital inclination/period space-frame and identifies the Abyss we have explored.

Early work on satellite coverage focussed on coverage of the earth's surface by single satellites. However, the problem of continuous, global coverage with multi-satellite arrays assumed greater importance for a number of missions, (missile warning, global weather, communications, etc.). The constellation designer is now facing a difficult set of trade-offs. In the LEO regime, a very large numbers of satellites are required to provide continuous global coverage. In some

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cases, arrays exceeding 200 satellites have been proposed. Such systems are easily shown to be very expensive, due to the large numbers of satellites (and boosters) required to establish them (and also to maintain them, through replacement). At the other extreme, near synchronous altitudes, a minimum of four satellites can provide continuous global coverage,[1] but due to the larger weights and increased energy required to reach GEO altitudes, such systems tend to be very expensive. A plot of the number of satellites required for continuous global coverage[2] is shown in Fig. 2. It would appear that at the curve extreme, systems costs rise inordinately. At the knee of the curve, in the mid-altitude range, a modest number of satellites may provide the requisite coverage, and since booster investments are much lower, total systems costs intuitively should reach a minimum in this region.

II. Introduction

The authors have attempted to quantify some aspects in the field of satellite coverage of the earth by making use of a subset of orbital space heretofore seldom explored, but which appears attractive from the standpoint of energy efficiency (and concomitant lower costs). We refer to this region of space as the Abyss, since it is large and virtually unpopulated. The approach used does not preclude the injection of all kinds of new technology in hardware improvements and miniaturization. Rather, all of these types of improvements combined lead synergistically to lower cost and higher performance systems in and of themselves. When combined with the use of improved orbital design, however, their effects are magnified. The attractive aspect of constellation design is that a reduction of the number of satellites required (by even a single satellite in some cases) represents a direct quantum drop in system cost!

In contrast to systems requiring continuous coverage of the globe or a specific geographic region, numerous systems are being considered which are intended to provide only partial coverage. Dr. John Hanson has published an excellent paper covering this topic for circular-orbit LEO constellations up to 650 nm altitude.[3] Partial coverage constellations will commonly occur for several reasons. First, during the build up phase (to a continuous coverage array) one must pass through a 'partial coverage' stage or stages. As an example, the GPS system has been evolving over the past fifteen years, and the constellation is still not complete. Second, some requirements may be satisfied by only a partial coverage (frequent revisit) as for weather, landsat, or other surveillance functions. And third, economic factors may limit system coverage to partial, when continuous coverage is actually desired.

III. Non-dimensional Coverage Parameter

In order to evaluate satellite coverage quantitatively, a non-dimensional coverage parameter (N_d) was developed using Buckingham's Pi Theorem[4]. Input parameters for N_d are: the total velocity increment needed to achieve the orbit in question ΔV, the mean surface area of the earth covered by the satellite S, the slant range to the limit of visibility from satellite to earth d, and a standard time unit T which is the Schuler or Herget period of 84.4 minutes. Additional factors that affect the magnitude of S are the minimum elevation angle ε and the orbit eccentricity e. The expression for the non-dimensional parameter is then:

$$N_d = S/(d \times \Delta V \times T)$$

It can be seen by inspection that this parameter is non-dimensional, so that any consistent set of units may be used, and the same value of the coverage parameter will be obtained. Increasing the numerator factor, and/or decreasing one or more of the denominator factor(s) will result in a higher value of the coverage parameter. Any of the foregoing will indicate a higher efficiency for the constellation. Stated another way, these factors include a greater earth surface area covered, a smaller maximum slant range (implying smaller communications link margins, greater sensor resolution, etc.) and finally a reduction in the size of the booster required to orbit the given satellite. The Schuler period, being a constant, does not affect the parameter directly. It is clear that increasing any factor in the numerator is a "benefit" and increasing any factor in the denominator is a "detractor". Thus, we can use the parameter as an optimization tool: the larger the parameter N_d, the more efficient the system. It is very much akin to the sticker label on the new car giving the 'miles per gallon' on the open highway: the numerator, miles, is a benefit; while the denominator, gallons, is the detractor. Quite obviously, most people using their car to commute to work want to obtain the highest figure possible for the size car that fits their preference.

It may be of interest to explain how the velocity increment ΔV affects performance. We might approach the problem in simplistic terms, using Newton's Second Law, F=Ma. If we describe the acceleration as $\Delta V/\Delta t$, and then rewrite the Law, we obtain:

$$\Delta V = F \times \Delta t / M$$

A rocket engineer would recognize the numerator in the right hand term as the total impulse for a rocket stage. The entire right hand term is the total impulse per unit mass. Since the total weight (and cost) of a rocket of a rocket is very nearly proportional to its total impulse, it is obvious that a smaller ΔV results in less impulse per unit of mass orbited. This will allow us to use smaller boosters. Or, if the booster is a given, it will allow us to orbit heavier (and presumably more capable) or a larger number of identical satellites. We have every right to be pleased when the ΔV goes down, just as the motorist would be with a small, fuel efficient car for his commute.

For earth coverage purposes, the value of the elliptic orbit has probably been underestimated. Since there are two extra parameters for the orbital mechanic to play with, there is much more flexibility in designing constellations using elliptic orbits. For lower earth orbits, even small amounts of eccentricity can have significant advantages in coverage. The differences between apogee altitude and perigee altitude appear to be magnified for lower orbits. Intuitively, one would expect that the time average, or mean altitude for an elliptic orbit would be equal to that of a circular orbit of the same period (i.e., the semi-major axis a, minus Earth radius R_E). Battin[5] shows that the time averaged orbital radius is actually equal to $a \times (1+e^2/2)$. Thus, the time-averaged altitude of an elliptic satellite is $a(1+e^2/2)-R_e$, where R_e equals the radius of the earth. This increase in effective altitude affects two terms in the coverage parameter. The first term affected is the total surface area covered, S; the second term affected is the slant range, d. For satellites close to the earth, the area of the coverage circle (S) increases almost as the square of the slant range (d), so that the net effect of eccentricity will be a benefit.

A plot of the basic coverage parameter N_d is shown in Fig. 3, for the case where eccentricity, e, and minimum elevation angle, ε, both equal zero. The curve peaks at a value of 2.5 hr periods, which is equivalent to a satellite altitude of 1600 nm. Coverage parameters for the LEO, the GEO, and the Molniya/GPS classes of satellite should be compared with the highest, or optimum value, of the parameter. A typical LEO satellite at 300 nm altitude has an N_d of 0.1589; a 12 hr GPS satellite an N_d of 0.1174; and a 24 hr GEO satellite has an N_d of 0.0786. The optimum value of the parameter, in fact, for circular orbits with zero elevation angles, corresponds to altitudes lying between the majority of LEO satellites and the higher Molniya/GPS class (and of course far below the geostationary belt.) This is the region called the Abyss in Fig. 1.

Calculation of the coverage parameters for other than circular orbits, or for elevation angles other than zero can easily be carried out. Non-zero values for eccentricity and minimum elevation angles are prime examples. Sample orbit coverage parameter values presented in succeeding sections have been calculated using pragmatic assumptions for eccentricity and minimum elevation angle.

A very similarly shaped curve (to Fig. 3), representing area search rate in square km per hour, as a function of altitude (hence period) has appeared in the literature.[6] This curve does not consider the ΔV factor however, being limited solely to the geometry and sweep rate of the satellite. Interestingly enough, the maximum value of sweep rate coverage occurs for grazing angles at about 1080 nm (2000 km), somewhat below the present papers' coverage parameter maximum, but still above the altitude now occupied by the preponderance of the LEOs.

Another interesting effect involving ΔV is the fact that for the same period orbits, less ΔV is required for orbits with increasing values of eccentricity.[7] Although the perigee kick is larger (to obtain the higher apogee), the apogee kick is much less, so that the net effect is a reduction of ΔV as eccentricity increases. This can be used to increase the payload weight for a given period orbit over that obtainable for a circular orbit of the same period. An example will be given in the next section.

IV. 8-Hour Elliptic Array

A hypothetical five-satellite 8-hour period constellation having coincident and repeating ground tracks has been presented by the authors[6]. See Fig. 4 for a plot of the repeating ground track of this array. This array has been dubbed "Tinker Bell" due to its unique bell-shaped ground trace. Oriented so that apogees occur on the same longitudes as the world's most heavily populated regions (i.e., North America, Europe and Eastern Asia), it affords excellent coverage of these regions as well as continuous coverage of the Arctic and North Polar landscape. It would be particularly useful for communications and weather satellite systems. We have calculated the coverage parameter for one of these satellites and found it to be 0.1099 (see Fig. 5). Comparing it to a GEO (24-hr period) satellite whose coverage parameter is 0.0648, it is seen that the 8-hr satellite is 1.7 times as efficient as the GEO satellite. For this constellation (and the coverage parameter calculation) a minimum elevation angle, ε, of 10 degrees was assumed. Since this array is intended to favor a particular geographical region, using the fewest satellites (one version contains a total of five satellites), its economy is derived not only from the high value of its coverage parameter, compared to a GEO array, but the fact that it uses far fewer satellites than would be required with a LEO constellation giving comparable coverage. In addition, advantage can be taken of the savings in ΔV obtained by use of an eccentricity of 0.45 rather than using 8-hr circular orbits (e=0.00). The amount of payload increase in percent for various eccentricities is shown in Fig. 6: it is seen that with e=0.45 the increase in payload weight in orbit is on the order of 16 percent. It should be emphasized that the total system cost, in the end, will be determined by the value of the coverage parameter (indicating individual efficiency), the arrangement or design of the array, the total number of satellites in the array, and the cost per satellite.

Archimedes, a similar 8-hr elliptic array, but with higher eccentricity, has been recently proposed for a direct broadcast radio system in Europe.[8]

V. 2-Hour Lightsat Array

Another satellite array was developed by the authors in response to a military requirement to achieve the maximum possible partial coverage of Northern Hemisphere mid-latitude region with an eight-satellite co-planar array (to be launched on a single booster). A two hour period orbit was selected, to give repeating ground tracks after 24 hours. A 24-hr ground track is shown in Fig. 7. An eccentricity of 0.1 was used, giving a perigee altitude of 467 nm and an apogee altitude of 1336 nm. The critical inclination of 63.4 deg was selected to avoid rotation of perigee. The argument of perigee of 210 deg was selected so as to favor a mid-latitude region (rather than higher latitudes from 63 degrees to the North Pole). The value of the coverage parameter N_d was plotted (see Fig. 8) assuming a value of $\varepsilon = 5$ degrees. A significant improvement in coverage was noted in the Northern hemisphere, over that provided by circular orbits. The study showed that over 13 hrs of continuous coverage of the Washington DC area was provided with this constellation. An instantaneous coverage Mercator plot is shown in Fig. 9.

A commercial counterpart of this system has been proposed as ELLIPSO, one of the present contenders to satisfy the need for a public satellite cellular phone system.[9] This 24 satellite system also has a two-hour orbital period, but a slightly higher eccentricity (e=0.1541). The system would provide Radio Determination Satellite Service (RDSS) in addition to voice transmissions for mobile users.

VI. Impacts on Satellite Design

General

The same six orbit parameters which we exercise (like degrees of freedom) to optimize coverage and tailor to specific missions, can also be used to reduce the stress on satellite hardware design requirements thereby allowing us to build simpler and less expensive vehicles. Examining the Abyss for impact on satellite design has indicated that many performance parametric trade curves have a "knee" in this region which indicate greater performance improvement over this range than at the more conventional LEO or GEO extremes. The following section highlights some of these parameters and their general impact on design.

Solar Illumination

Two primary effects of solar illumination on spacecraft design are in its power and thermal subsystems. Solar cells have long been the primary source of power on earth orbiting spacecraft and solar heating is one of the primary factors affecting temperature control; both the total amount of time a satellite spends in the earth's shadow and the frequency and duration of each eclipse are important design considerations. LEO satellites (with worst case beta angles) may spend over eight hours per day in the earth's shadow [10] during periods up to 35 minutes per revolution. GEO satellites, on the other hand may spend over an hour per day while passing through the earth's shadow once. Figure 10 indicates both the maximum duration spent in the earth's shadow per day and per revolution basis. The eclipse duration as well as the frequency of these outages is more manageable for medium altitude orbits. Furthermore, unlike most conventional circular orbits we can use eccentricity to further reduce these outage periods thereby simplifying both thermal control and power system design.

Launch Vehicles

The inventory of US expendable launch vehicles has evolved to satisfy the demands of conventional satellites in traditional orbits. We must consider the issue of whether standard boosters could be used to launch satellites in these new orbits. Fortunately our ability to develop smaller, lighter, and more efficient satellites has provided the additional launch margins to take these payloads into higher orbits. A Delta II-7920, for example, could deliver a 2000 lb satellite into most of the orbits discussed in this paper.

Orbit Maintenance

The dominant orbit perturbation forces (J_2 & J_3 Earth harmonics terms) vary primarily with altitude and are generally more severe for LEO. Medium altitude satellites can increase their eccentricity moderately without as severe station keeping penalties to maintain placement of critical nodes. Furthermore, unlike the case of GEO satellites, the GPS constellation can be used by satellites in medium orbits for on-board autonomous navigation.

Link Margins

Ground communication with satellites has been an problem strongly dependent on the satellite's altitude and inclination. The current interest in smaller ground receivers has placed a greater burden on satellite power to close the communication link. Electronic attenuation due to range is less for LEO satellites than conventional GEO communication satellites, but this lower altitude also reduces the average pass duration to less than 10 minutes. Areas of mutual coverage are greatly reduced. Lower, faster satellites increase the difficulty of tracking by terminals and increase the effect of doppler. Geostationary satellites provide more uniform coverage with no tracking problems but their significantly greater range increases both transmitter power and receiver sensitivity requirements. When considering factors such as slant range, coverage (allowing for minimum elevation), and ground to satellite dynamics, once again medium orbits fall into the knee of the design curve (Fig. 11)

Environment

The utility of orbits in the Abyss may have been overlooked in the past due to the perceived hostility of that environment principally from the effects of radiation. However, more recent measurements of the radiation belts coupled with improved technology for dealing with the effects of radiation on spacecraft have suppressed this argument. Furthermore, the absence of traffic in the Abyss has kept this region relatively clear of debris, unlike the situation in the LEO and the GEO bands.

Radiation

The Van Allen radiation belts have long been a deterrent to closer consideration of possible orbits in the Abyss. Current estimates of the electron flux ($\log_{10}$ of flux with energies over .5 MeV at the equator) for orbits in the 1200 to 8000 nm range varies from 7 to 5.3. The flux at GEO is approximately 5.3 and high satellites at the higher end of the LEO range experience a similar range of values as in the Abyss (Fig. 1). The proton flux similarly peaks in the Abyss (Fig. 15), but the orbit design trade space we have discussed in this paper can also apply three of the six degrees of freedom to both optimize operational coverage and to reduce the severity of radiation effects on satellite design. In some of the specific cases we examined, the net radiation effects were less severe than those experienced by Molniya satellites. In addition the radiation induced impact to solar array degradation for one case we ran, indicated half the degradation rate indicated by the generally accepted "rule of thumb" charts in most satellite design handbooks.

Recent radiation measurements being analyzed by AFGL have resulted in a more accurate estimate for the use of this region. By accurately mapping this region they have reduced some of the conservatism of previously accepted models. Furthermore, electronics technology has made significant progress toward making available more radiation tolerant components. This will allow more spacecraft to operate in these previously forbidden regions. These advances in space technology and environment definition have allowed us to reopen this design space. We plan to continue to assess the impact of radiation on candidate orbits.

Debris

The Office of Technology Assessment estimates that by the year 2000 to 2010, some over-populated low earth orbits may become too risky to use due to a unacceptably high likelihood of collision with debris. Other unique orbits such as those in the GEO belt also are vulnerable to similar collision and contamination hazards due to a growing debris population. The OTA has proposed that steps be considered to stem the rate of debris growth in these high traffic areas, but like terrestrial litter, reducing the future growth of debris and cleaning up the pollution problem of decades past are two different issues. The Abyss, like unsettled territories, could avoid similar debris issues simply by adopting appropriate preventative measures. The trade space in the Abyss, unlike the GEO or LEO examples, has a broader geometry within which to work, thus making the debris issue easier to manage.

VII. Summary

In summary, the design of satellite constellations is highly dependent on the requirements (or 'design specs') laid down by the user or client. Having said this, it is becoming apparent that the Abyss, the mid-altitude region of space (lying between the lower-orbiting inclined LEOs or polar LEOs and the high altitude circular equatorial GEOs), is virtually unused territory. Yet, it is also the region in which the potentially most efficient constellations (from the standpoint of coverage vs cost) are to be found. The use of elliptic orbits allows much more flexibility for providing maximum coverage of specified geographic areas. Further, the incredible crowding being experienced at the GEO equatorial belt might be greatly alleviated by employing this new design space. These newer elliptic orbit constellations in the Abyss region require considerably more complex calculations and design effort to optimize; however, with modern computers this task becomes much easier. The modern trend towards increased miniaturization and smaller, lighter satellites can be combined with the newer techniques for constellation designs. The resultant space systems synergistically using both of these new technologies should prove to be much more efficient at providing their intended services, as well as much less expensive. They may, in fact, change the traditional ways of deploying multi-satellite constellations, allowing a more even spatial distribution of satellites around our planet.

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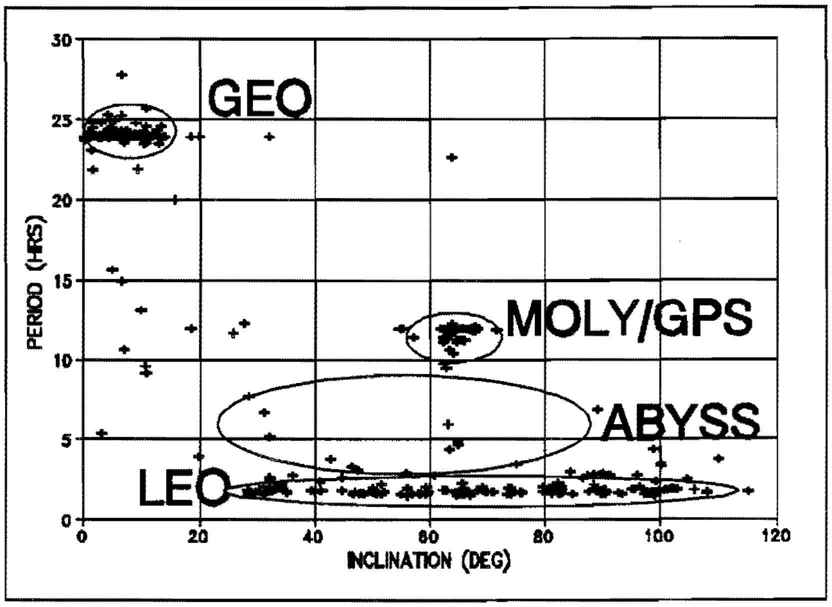

Figure 1
Plot of the distribution of over 1600 satellite payloads to depict their tight grouping within three bands (LEO, GEO, and Molniya/GPS) and the void in the region we refer to as the Abyss.

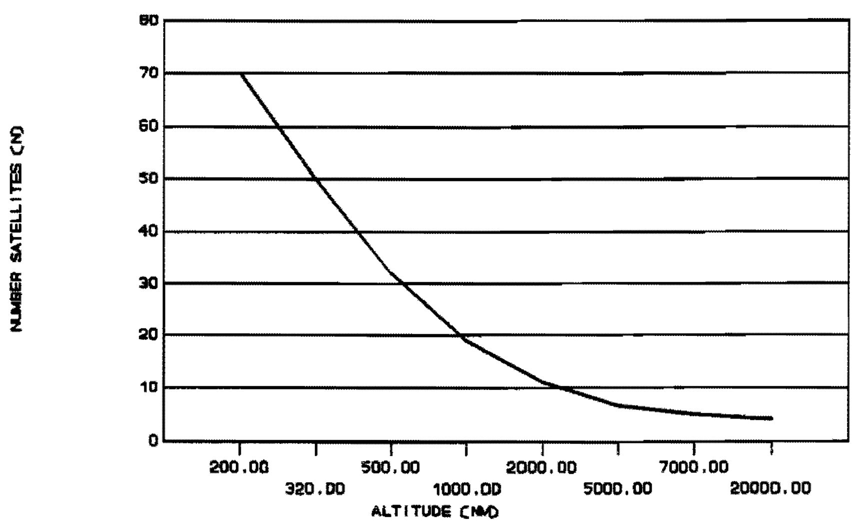

Figure 2
The number of satellites required for continuous single global coverage vs altitude.

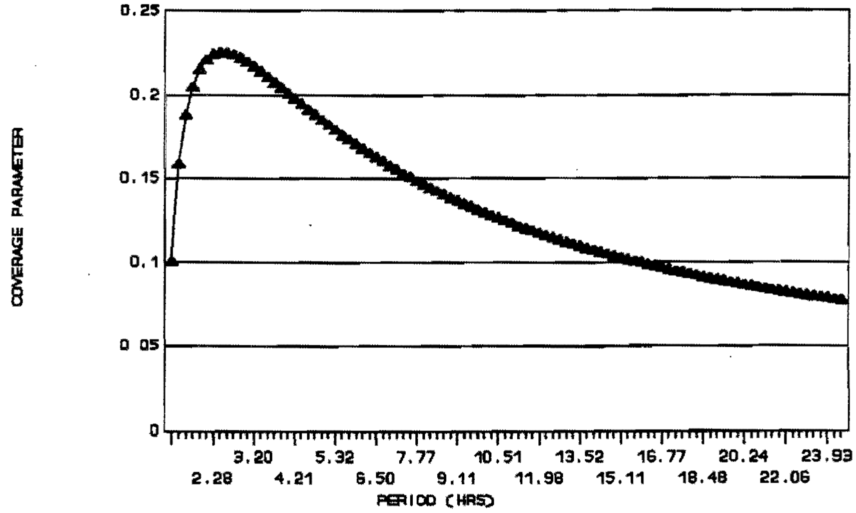

Figure 3
Coverage parameter (N_d) for Orbits with e = 0 and ε = 0.0

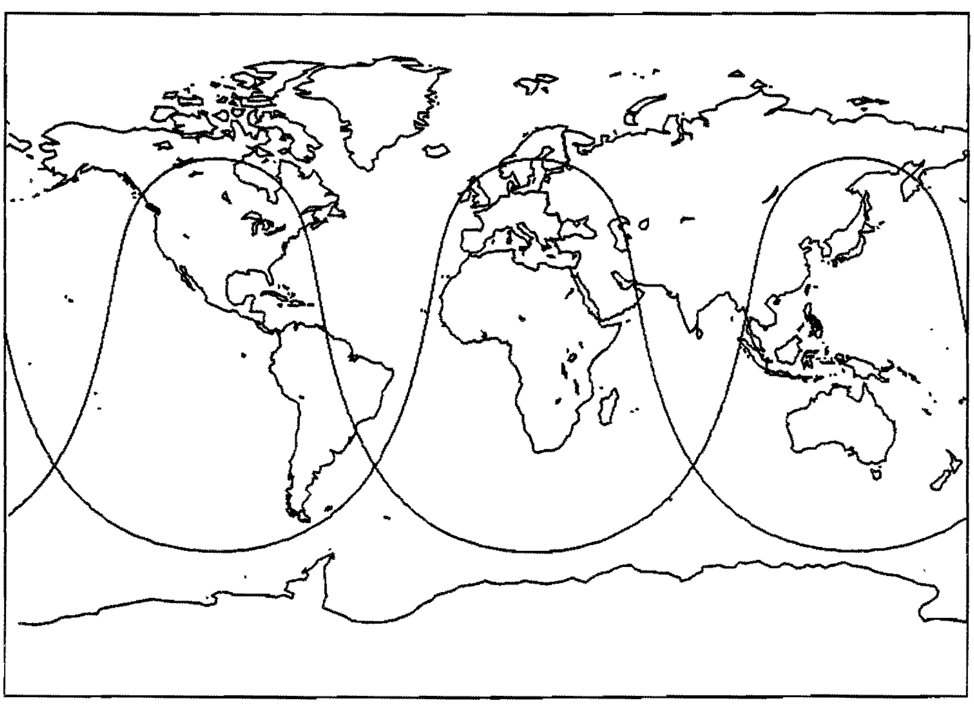

Figure 4
"Tinker bell" orbit with 8 hour ground track and e = 0.45

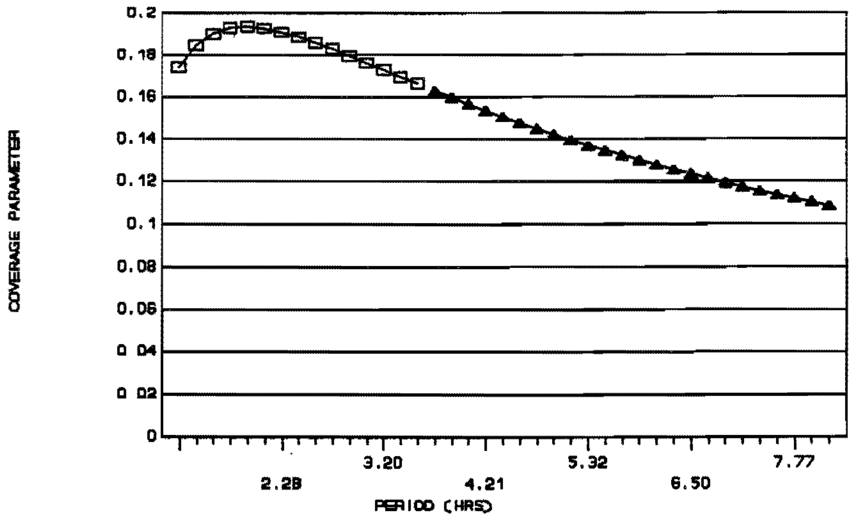

Figure 5
Coverage Parameter, (N_d) e = 0.45 and ε = 10° Square symbols indicate "impossible orbits" (perigee below 200 nm); Triangular symbols indicate practical orbits.

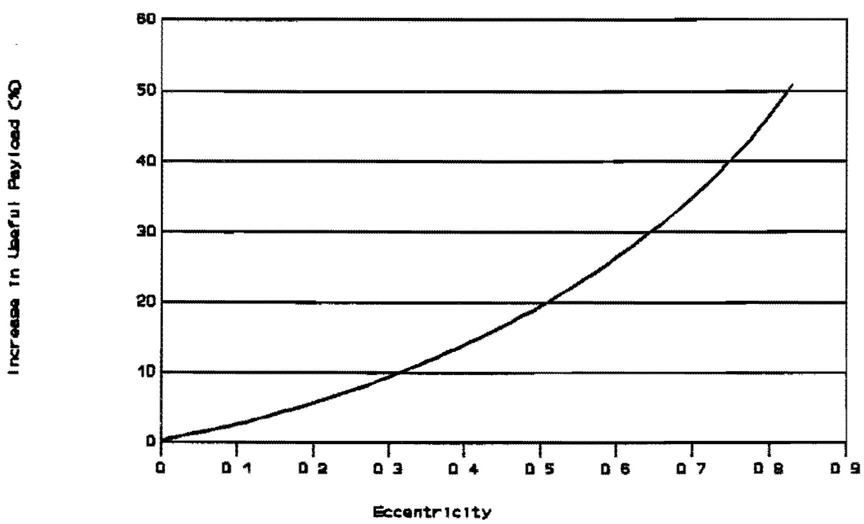

Figure 6
Percentage increase in useful payload as a result of increasing eccentricity (Period = 8 hours)

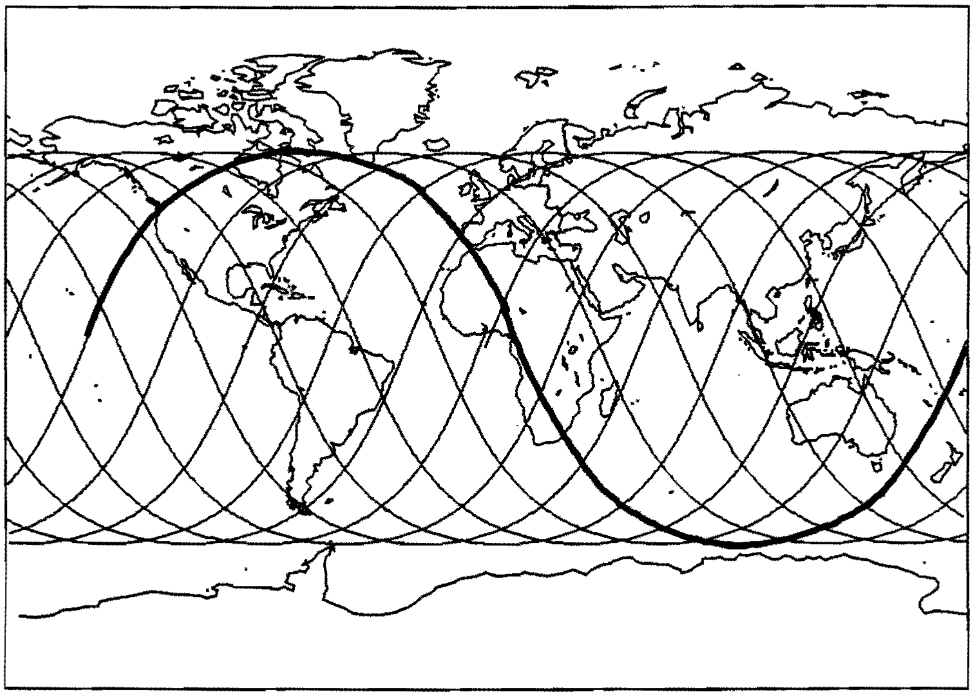

Figure 7
Two hour COMSAT with repeating ground tracks; $e = 0.1$, $\varepsilon = 5^{\circ}$, $\omega = 210^{\circ}$

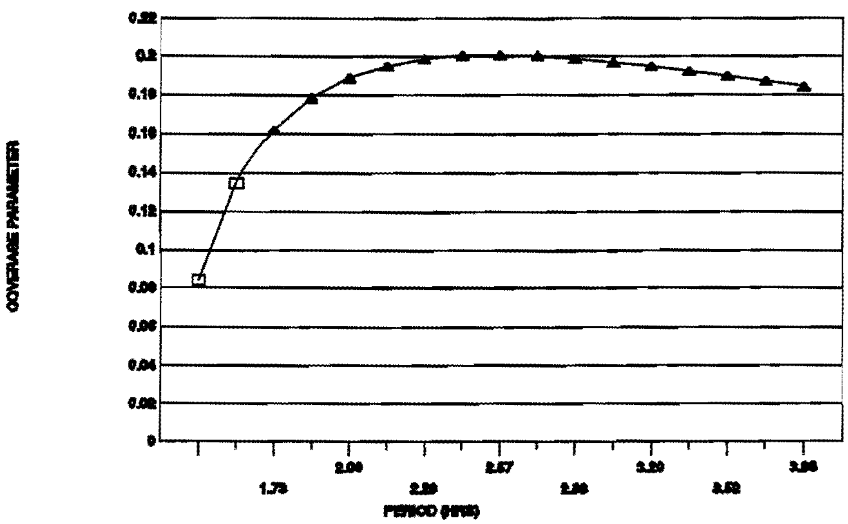

Figure 8
Coverage Parameter, (N_d) for $e = 0.1$ and $\varepsilon = 5^{\circ}$

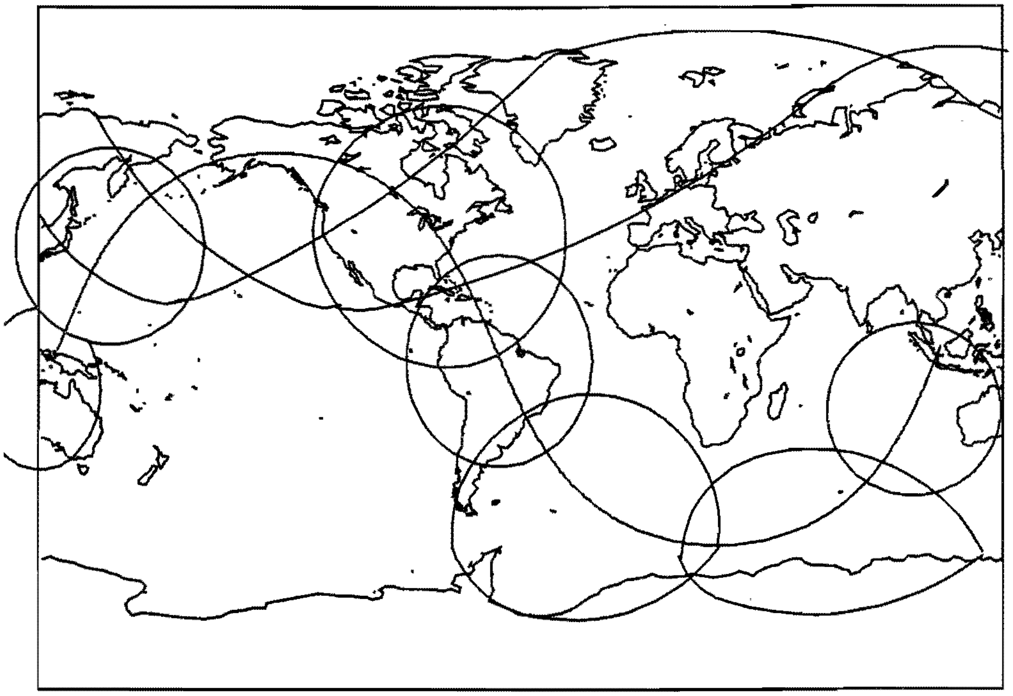

Figure 9
Two hour, eight satellite, partial coverage array showing instantaneous coverage.
$e = 0.1$, $\omega = 210°$, and $\varepsilon = 5°$

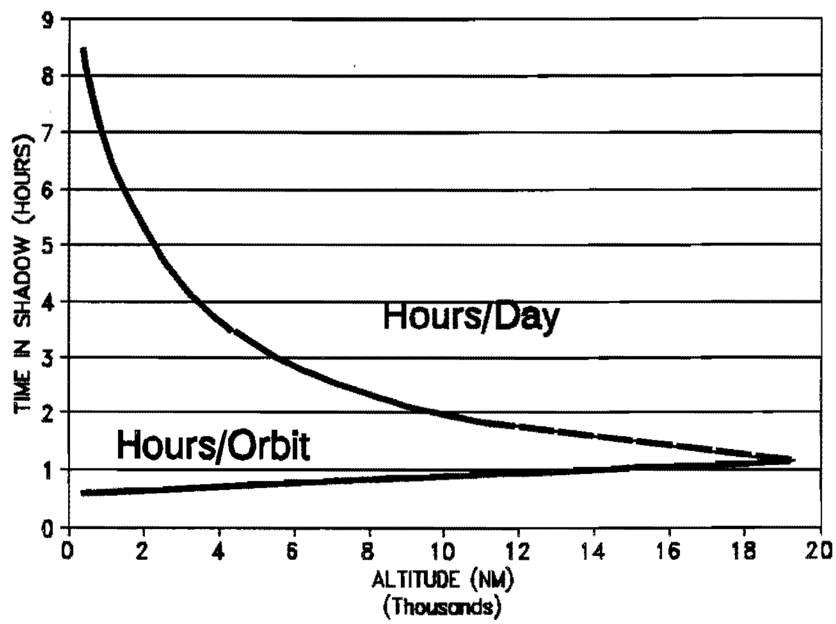

Figure 10
Worst case effect of earth's shadow on circular orbits indicating both maximum outage per day and maximum outage per orbit revolution.

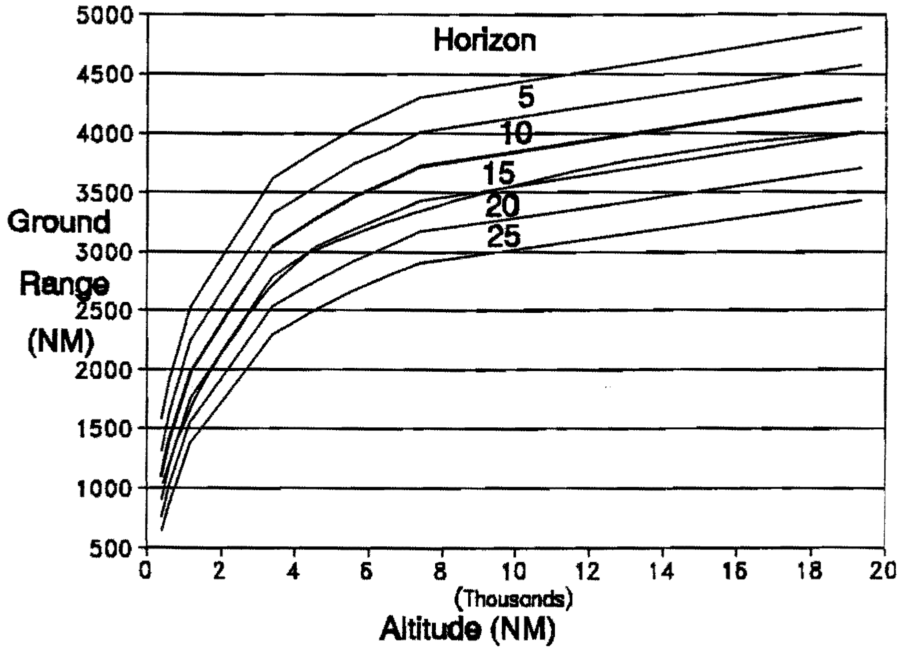

Figure 11
These curves show how coverage increases with altitude. Each represents the radial distance to an observer for 0, 5, 10, 15, 20, and 25° minimum elevation angles respectively. Another demonstration that the Abyss is at the knee of the curve!

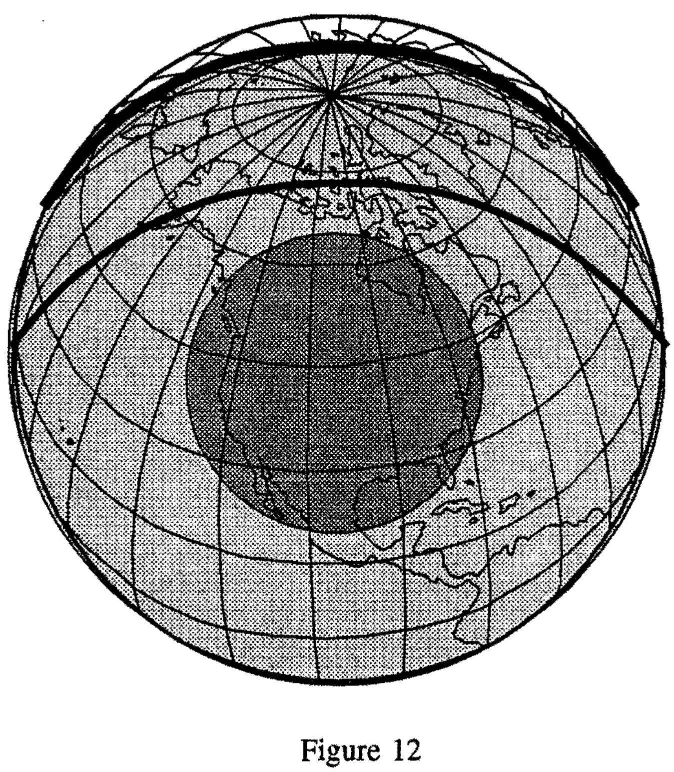

Figure 12
Earth coverage of three orbit altitudes (for 10° minimum elevation angle). Small circle is for 400 nm altitude, next line indicates GEO, northern most line indicates "Tinker-bell" orbit near apogee.