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The ELLIPSO^{TM} Satellite – Application of Small Satellite Principles to the Space Segment of a Global Mobile Personal Communications System

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Abstract. The designers of ELLIPSO have intentionally driven the design of their satellites towards simplicity, and thus lower cost. The service link antennas are state of the art fixed planar arrays mounted on a nadir pointing plane that is always oriented towards the center of the earth. The communications payload uses simple, bent-pipe transponders to avoid the necessity of extensive onboard digital processing. The level of major component redundancy in each satellite is much less than in their more expensive GEO comsat cousins. The effect of a satellite failure is not so severe for ELLIPSO as for a typical GEO satellite for two reasons. First, failure of one satellite out of a system of 17 (the total in the ELLIPSO system) is much less percentage-wise, than the failure of a single GEO that may represent the entire system, or one in a group of two or three satellites. Second, the planned lifetime of the less expensive ELLIPSO satellites is shorter than that typical of GEO satellites. Scheduled launches for system replacement will occur earlier and more often than for GEO systems. Also, replacement of a single ELLIPSO satellite requires a much smaller launch vehicle than a GEO (due to its lower elliptic orbit). In short, the ELLIPSO satellites bear a closer resemblance to their smallsat cousins than they do to the conventional, larger and more complex GEO communications satellites.

Introduction

At the present time, the world is seeing an extremely rapid growth in the numbers and varieties of non-geostationary global mobile communications systems. Some of these systems use very small size satellites (tens to a few hundreds of kilograms) primarily for data-only services, and these are often referred to as "Little-LEO" systems. Those systems providing both data and telephone communications, of which ELLIPSO is an example, are referred to as "Big-LEO" Systems. Even though the ELLIPSO system is a "Big-LEO" system, it can trace much of its heritage to developments first pioneered in the small satellite arena. Compared with the trend towards extremely heavy GEO communications satellites, the 1000 kg ELLIPSO satellite can be considered 'small'. Another major distinguishing factor separating LEO and MEO communications satellites from communications satellites in geostationary orbits is their relative simplicity. Consider, for example, the complex antenna beam patterns of the GEO satellite, tailored to fit the outlines of continents or coverage areas. The incorporation of dozens if not hundreds of transponders in typical GEO satellites certainly qualifies them for achieving a high level of complexity.

The goal of the Big-LEO communications satellites is to provide customers with cellular (hand-held) telephonic and data communications globally. This is to be achieved using relatively simple low- to medium altitude satellites that can more readily close the link margins required for low-powered handset terminals transmitting less than one watt of electrical power.

In 1992, Mr. Tom Kacena and the present author proposed avoiding the crowded ring of satellites in the geostationary ring, and also the imminent overpopulation in the relatively thin shell of circular LEO orbit systems at altitudes below 1000 nautical miles. This could be accomplished by constructing elliptical systems, (i.e., "populating the abyss").[1] This strategy would assist in: (1) reducing electronic interference in general, (2) reducing the perturbing effects of atmospheric drag, (3) reducing the likelihood of damage by orbital debris, and finally, (4) reducing the mathematical probability of satellite-to-satellite collisions.

Satellite Simplicity

The designers of ELLIPSO have intentionally driven the design of their satellites towards simplicity, in order to achieve lower cost.[2] The user link antennas are relatively simple, state of the art fixed planar arrays mounted on a nadir pointing plane that is always oriented towards the center of the earth. The communications payload uses simple, bent-pipe transponders. The advantage to this approach is that most of the system complexity is located on the ground at the gateway Ground Control Stations (GCS) and the TT&C stations (where components and software can be easily and readily modified or updated). Figure 1 shows the satellite; note the two planar array antennas for the user links (up and down). The same satellite design is used for the BOREALIS™ sun-synchronous inclined planes and the equatorial CONCORDIA™ circular-orbit planes- the apogee altitudes of the former approximating the circular altitudes of the latter.

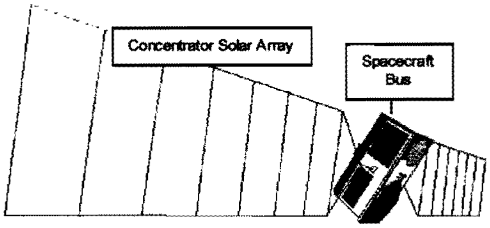

Fig. 1 ELLIPSO Satellite
(Solar Array Deployed)

In August 1988, a DARPA contract was with Defense Systems, Inc., for two UHF store-and-forward satellites weighing about 140 pounds each. They were named Multiple Access Communications Satellites (MACSATs) to describe their intended function- providing message relays to tactical forces in the field. One of the satellites died prematurely, but the other was very successful. In fact supported Marine Corps forces in both Desert Shield and Desert Storm. This MACSAT satellite could be considered the precursor to most of the present and planned Little-LEO communications systems (e.g., Orbcomm).

In 1991, the Defense Advanced Research Projects Agency (DARPA) launched seven small experimental Microsat satellites weighing approximately 50 pounds each, on a Pegasus launch vehicle. Although a partial failure of the Pegasus resulted in a lower than nominal altitude, the satellites themselves operated successfully for six months before deorbiting (at the nominal altitude they would have been in orbit for about two years). These seven Microsat satellites (not surprisingly named after Snow White's seven dwarfs!) successfully demonstrated a real-time wireless telephony capability at 2.4 kbps as well as a store and dump data capability for messages up to 24 kilobits, both for use by tactical military commanders. Thus, one might conclude that this DARPA program was a precursor to the later commercial Big-LEO systems, doing approximately the same things but having much more capacity. The Big-Leo systems that filed with the FCC were ELLIPSO, Iridium, Globalstar, Odyssey, and Constellation.[3] In the initial filings, the satellite masses varied from about 600 to 1500 kg.

The level of major component redundancy in each ELLIPSO satellite is much less than in their larger GEO cousins. The effect of a LEO satellite failure is not so severe as in a GEO for two reasons. First, failure of one satellite out of a system of 17 (the total in ELLIPSO) is much less percentage-wise, than the failure of a single GEO that may represent the entire system itself, (or possibly be in a group of two or three satellites). Second, the planned lifetime of the less expensive ELLIPSO satellites is less than is typical for GEO satellites. This means that scheduled multiple satellite ELLIPSO launches for system replacement occurs earlier than for GEO systems. If required, the immediate replacement of a single ELLIPSO satellite, would make use a much smaller launch vehicle (carrying less satellite mass to a lower altitude orbit).

On-Board GPS

ELLIPSO satellites may carry small on-board GPS receivers, whose readings will be relayed back to earth for precise orbit determination and for the calculation of stationkeeping maneuvers. GPS receivers have been carried on several smallsats, including the POSAT and SNOE satellites, as well as on the larger TOPEX-POSEIDON satellite. The use of GPS (giving a few position/velocity readings per orbit) allows for a highly automated process of orbit determination. This would lessen manpower requirements, as well as improving the accuracy, over more traditional OD methods. A "micro-GPS" developed by JPL is now being flown on the SNOE satellite; it will provide 200 m orbit accuracy with less than 1 kg mass and less than 0.1 watt average power.[4] A follow-on by JPL will be flown in the STRV-1C satellite in 1999.[5]

Batteries/Solar Arrays

MCHI has been investigating new technology approaches for power system components. Among these are the new nickel-hydrogen type batteries, as well as concentrator type solar arrays. AEC-Able Corporation has developed the Scarlet solar array that employs a Fresnel lens system to effectively concentrate the sun's rays onto the collector area.[6] An early prototype intended to meet ELLIPSO requirements was on the Comet satellite, that was unfortunately lost with the failure of the Conestoga launch vehicle at Wallops Island.

Constellation Optimization

Although the design of elliptical constellations is considerably more difficult than the design of circular (i.e., Walker, or Beste type systems), the many advantages justify the extra design effort. The engineering development dollar can be repaid many times over through reduction in the number of satellites and launch vehicles. One must look at total system life cycle cost as one of two major factors in the design of an efficient system- the other factor being the maximization of system performance.

An indication of the relative efficiency of elliptic versus circular orbit constellations may be seen in Figure 2.[7] The plot shows a definite advantage in favor of the elliptical orbit ELLIPSO system, over the circular orbit constellations. Less ΔV is required for elliptical systems, and also fewer satellites.

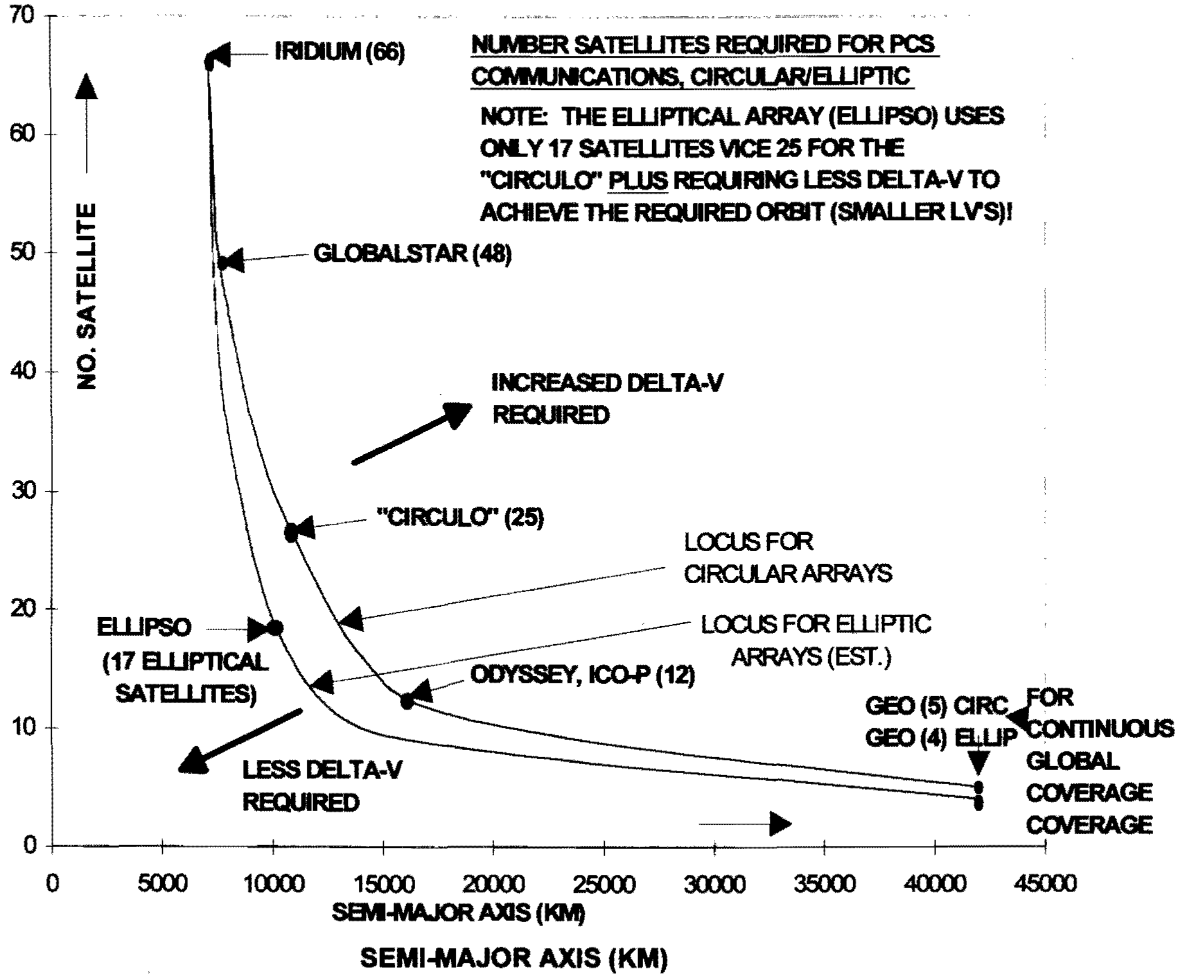

Fig. 2 Number of Satellites Required for continuous Coverage (Circular vs Elliptic Orbit Systems)

By choice, we would like (1) to be located towards the 'knee' of the curve (whether the array is circular or elliptic), and (2) on the elliptic instead of the circular locus (since fewer satellites are required with elliptic).

Optimum Satellite Altitude

Number of Satellites vs Altitude

A very important question arises in designing a new constellation – i.e., "What is the best operating altitude?" Obviously, all of the Big-LEO developers have answered this question with "Less than GEO.....", but there remain considerable differences between them. The lowest of these systems is Iridium; with its circular altitude of 780 kilometers 66 satellites are needed for continuous global coverage. The Globalstar system at 1414 kilometers circular requires 48 satellites. The European ICO system at 10355 kilometers employs 12 satellites. Finally, the ELLIPSO system, which is actually a hybrid elliptical/circular constellation, employs two sun-synchronous elliptic planes of 5 satellites each, and a circular equatorial plane with 7 satellites for a total of 17 satellites. The semi-major axes of all three planes effectively places ELLIPSO in between the two LEO systems (Iridium and Globalstar) and the MEO ICO system. It is interesting to note that both ICO and Odyssey (the latter merging with ICO last year) conducted trade studies and determined that their 10355 km altitude resulted in a lower system total cost than either a LEO (<1000 km) or a GEO system. One might well ask whether there is some other intermediate altitude even more efficient than ICO's 10355 km value.

The Draim Number

The author has developed a simple non-dimensional parameter to help answer the question posed in the paragraph above. From a purely mechanical viewpoint, this parameter strikes the best balance between (1) the maximum slant range (from satellite to ground terminal); (2) the ΔV impulse required to achieve final orbit; and (3) the surface area of the earth covered. The formula for this non-dimensional parameter is:

$$N_D = S / (d \times \Delta V \times T) \qquad (1)$$

where,

S = Area of satellite footprint on the earth;

d = Maximum slant range (from the satellite to the edge of the footprint);

ΔV = Total impulse to orbit satellite, and;

T = The period of a sea-level satellite (i.e., the Schuler or Herget period = 84.5 min),

expressed in any consistent set of units.

This parameter, N_D, is usually maximized for satellite periods of 2.5 to 4 hours, with parameter values slightly higher for elliptic than for circular orbits. A plot of N_D for both circular and elliptic orbits, for 20 degree minimum elevation angles and 500 km minimum perigee heights (for the elliptic orbits) is shown in Figure 3. It is necessary to note that not much eccentricity can be tolerated at low apogee altitudes; a plot for perigee heights of 500 km showing the allowable eccentricity versus satellite period in hours is shown in Figure 4. An interesting but apparently little-known fact is that it actually takes less ΔV to orbit a 3-hour elliptic satellite than it does to orbit a 3-hour circular satellite! Also, note how rapidly the value of the parameter decreases for satellite (and likewise constellation) altitudes below 2500 km.

The non-dimensional parameter N_D most likely understates the elliptic advantage. It considers total earth coverage, total delta-V, and so forth, without quantifying the fact that the elliptic coverage can be targeted to certain geographical areas and local times of day.

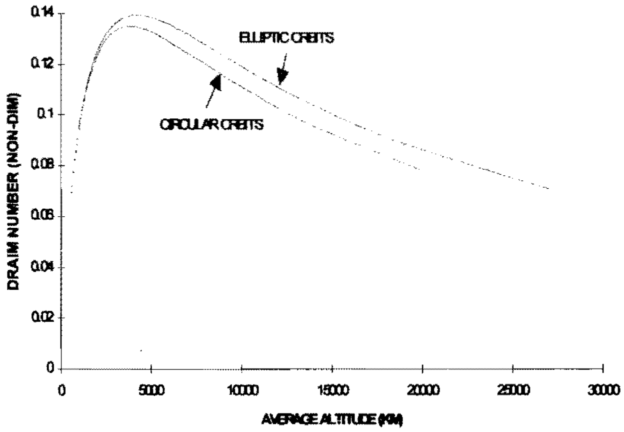

Fig. 3 Draim Number, N_D
(All satellites with 20 deg minimum elevation angles; Elliptic Satellites with 500 km perigees;

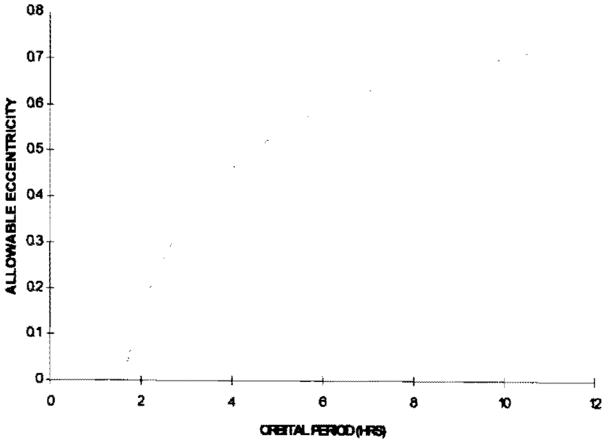

Fig. 4 Allowable Eccentricities, 500 km perigees

The ELLIPSO Constellation

The ELLIPSO system has been optimized for earth coverage through use of a unique, patented constellation that includes both elliptical and circular communications satellites.[8,9] The ELLIPSO constellation is shown in Fig. 5. The use of elliptical orbits permits the biasing of earth coverage by latitude and time of day so that satellite coverage can be well matched to the market needs for particular geographical regions and normal day-night usage patterns. The ELLIPSO constellation's earth coverage performance is continually being improved through adjustments to the orbital parameters. Additionally, more efficient methods for the orbital insertion, phasing and station-keeping of ELLIPSO satellites are being developed, as an ongoing process. The design of the ELLIPSO system's constellation is viewed as a major technological advance in the field of non-GEO communications satellite systems, and is considered by many as superior to the other Big-LEO circular orbit systems.

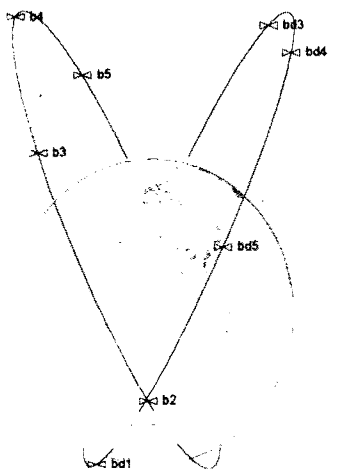

Fig. 5 The ELLIPSO Constellation

Conclusions

The newer commercial communications satellite systems (Big- and Little LEOs) are beginning to take form, and it is evident that they owe much to new concepts and technologies first demonstrated by the smallsat community. It is the firm conviction of the author that the increased flexibility provided by opening up the design space to include all types of orbits including elliptic arrays, at altitudes between very low earth orbit and the geosynchronous band will bring great benefits. The ultimate beneficiary will be the ordinary consumer-he will benefit from lower communications costs as these systems become more mature and are more completely optimized. The main burden will be on the engineering team that is asked to accomplish this demanding task.

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