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Demonstration of the COBRA Teardrop Concept Using Two Smallsats in 8-Hour Elliptic Orbits

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ABSTRACT: Space Resource America Corporation is engaged in developing new concepts for communications satellite systems that will avoid interference with any of the Geostationary satellites and can provide a significant increase in global capacity compared with that of the GEO ring. Additionally, since all satellites in such a system are flying in formation, they will not interfere with each other. The company has filed for a series of patents on the orbital arrays, or constellations, that appear to hold the most promise in satisfying both commercial and government requirements. Each of the three active arcs of a single 8-hour satellite has a ground trace that resembles a coiled COBRA, and the orbits were so named. The acronym-like name COBRA was later amplified to "Communications Orbiting Broadband Repeating Arrays". One of these arrays employs six 8-hour period leaning elliptical orbit satellites describing three continuous closed paths in the Northern Hemisphere. Ground antennas follow these satellites as their active arcs describe a repeating teardrop-shaped closed path in the sky. The tracking rate is very slow- averaging about 10 degrees/hour. It is possible to demonstrate all of the features of this array, however, with only two satellites. SRA is planning such a demonstration using two smallsats with a limited broadband communications payload. The communications payload will operate at Ku band or higher. The repeating ground tracks of this planned satellite duo will allow for an 8-hour demonstration daily in each of three Northern Hemisphere regions. The three teardrop shaped loops are separated in longitude by 120 degrees. One teardrop is centered upon the United States, the second on Japan and eastern China, and the third on central Europe. Conveniently, each regional demonstration will begin and end at the same local time of day. The use of smallsats for this demonstration is very desirable, in order to hold down costs of both satellites and launch vehicles. The design lifetime of the satellites will be approximately six months to a year, with the satellites being de-orbited at the appropriate time.

Introduction:

Space Resource America Corporation is currently engaged in developing advanced satellite constellation concepts for next-generation satellite communications systems. SRA's COBRA Teardrop Array (Pats. Pending) represents one example of such a new approach using elliptical orbits. Its genesis lies in an earlier SRA development named "COBRA" due to the shape of its active arc on a map of the world (Pats. Pending). A prime requirement for both of these systems is that they not interfere with the established ring of GEO satellites. Complete coverage of the entire Northern Hemisphere requires only six of the SRA basic COBRA satellites or just six of the COBRA Teardrop satellites, in 8-hour elliptical orbits. A working demonstration of the Teardrop concept is planned that will use only two smallsats. This demonstration will actually provide 8 hrs of continuous coverage, sequentially, to each of three Northern Hemisphere market regions spaced 120° apart in longitude.

A Brief Background on Elliptical Arrays:

The principal advantage of the GEO (Geostationary circular) orbit is that the satellite appears to be nearly stationary in the sky. Therefore, the ground station antennas have a very easy job; they just need to stare in one direction.[1] A major disadvantage of any GEO satellite results from its orbiting over the Equator. As users move higher in latitude, the elevation angle to the GEO satellite becomes less and less, until at 75° to 80° of latitude the satellite disappears below the observer's horizon.

In April 1965 the first 12-hour elliptical Molniya communications satellite was launched by the Russians.[2] The fundamental concept of their highly elliptical Molniya orbit was to force the satellite to spend long periods of time over the higher Northern Hemisphere latitudes. A typical Molniya orbit lingers over Russia for approximately eight (8) hours per day. By carefully positioning the satellites in sequence, as few as three (3) satellites can provide continuous coverage of the entire (then Soviet Union) land mass.[3] All Molniya orbits have orbital inclinations of approximately 63 degrees in order to reduce or eliminate rotation of the line of apsides (major axis of the ellipse) due to gravitational perturbations.[4] This prevents their apogees from drifting away from their initial latitude. The Russian Molniya orbits had arguments of perigee at or near 270 degrees so that the resulting coverage was highly biased to the northern latitudes. Molniyas also had repeating ground tracks, ensuring steady coverage with only moderate station-keeping.

Since their introduction, large numbers of both the GEO's and the Molniya's have been orbited. Western nations mostly favor the GEO satellites, while the Russians have used a mix of both Molniyas and GEOs.

In recent years, however, new paradigms for communications satellite constellations have been developed. Rather than operating with individual GEO satellites, multi-satellite Walker and Beste type constellations were designed and in some cases placed in orbit (Iridium, Globalstar, Orbcomm). In the equatorial plane, elliptical orbits can be designed having their apogees always pointing to the sun (APTS orbits)[5,6]. This increases the daytime coverage capacity (at the expense of night-time coverage). These elliptical equatorial orbits can be interleaved with circular equatorial orbits to provide controlled augmentation to daytime capacity (the "Gear array")[7]. The Ellipso satellite telephony system combined some features of both the GEOs and Molniyas in a unique, hybrid constellation.[8] It was designed to provide continuous coverage from the North Pole to 55 degrees South latitude. In Ellipso, two planes of leaning, elliptical sun-synchronous orbits were used, with periods of approximately three hours and apogee altitudes of 7846 km. These two inclined orbital planes remained edge-on to the sun year round, with the apogees slightly favoring the sunlit hemisphere (thus biasing coverage towards daytime hours). The third plane used circular equatorial orbits at 8040 km altitude to give tropical and southern hemisphere coverage. The problems experienced by the Iridium and Globalstar systems, coupled with the global economic downturn, made it virtually impossible to attract sufficient investment capital for this type of system. In June 2001, the Federal Communications Commission revoked the license for the Ellipso system, due to failure to meet its construction milestones.[9]

Other new paradigms in elliptical orbit constellation design have been introduced. In 1992, Draim introduced the eight (8) hour elliptical orbit constellation named TinkerBell.[10] Maas also studied the eight (8) hour orbits and displayed the ground tracks associated with leaning these orbits.[11] Ulivieri investigated the application of shorter period elliptical orbits, including a five (5) hour orbit with eccentricity of 0.5, inclination of 60 degrees and argument of perigee of 180 degrees.[12]

These new elliptical orbit constellation designs have started to make their way into commercial constellation design.[13] Two FCC filings for elliptical broadband communications systems were made in January 1999. These were the Virgo system (for 'Virtual GEO') submitted by Virtual Geosatellite LLC, and the Pentriad system, submitted by the Denali Corporation. Space Resource America Corporation is not associated with either of these two corporations. The US Sirius digital audio radio system (DARS), which plans to commence operations this year, uses a 24-hour elliptical orbit constellation with three satellites in a repeating ground track centered on the North American market.

Elliptical Orbit Basics

It should be pointed out that 63.4 degrees represents the "critical" inclination for elliptical orbits. At any other inclinations, the line of apsides (major axis of the ellipse) will rotate within the orbital plane, causing the apogee and perigee latitudes to drift. The stability of the line of apsides is necessary, when designing constellations that will match increased coverage, or capacity, to high interest market regions, and maintain this relationship over time.[14,15]

Most elliptical arrays use a 90° or 270° argument of perigee, or angles within ten degrees of these two values. This places the apogees at or very near the maximum latitudes defined by the inclination angle- 63.4 degrees South or 63.4 degrees North latitude respectively.

A significant variation in the appearance of a repeating ground track elliptical orbit is very evident when using other than a 90° or 270° argument of perigee.

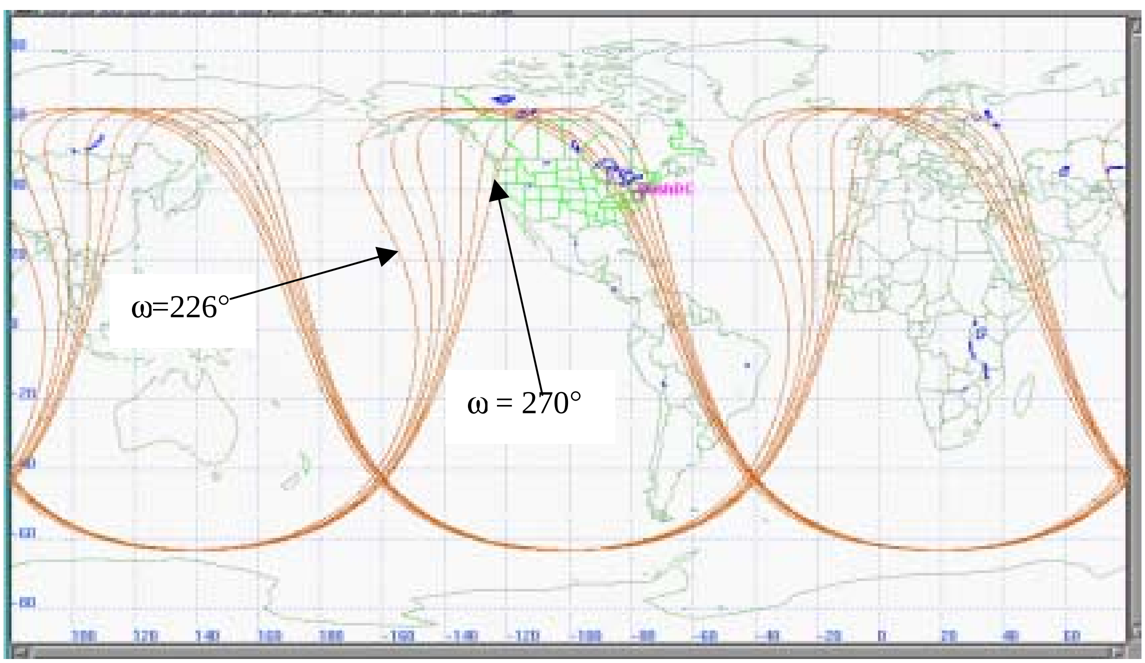

Figure 1
8-Hr Elliptic Ground Tracks with Varying Amounts of "Left Lean"

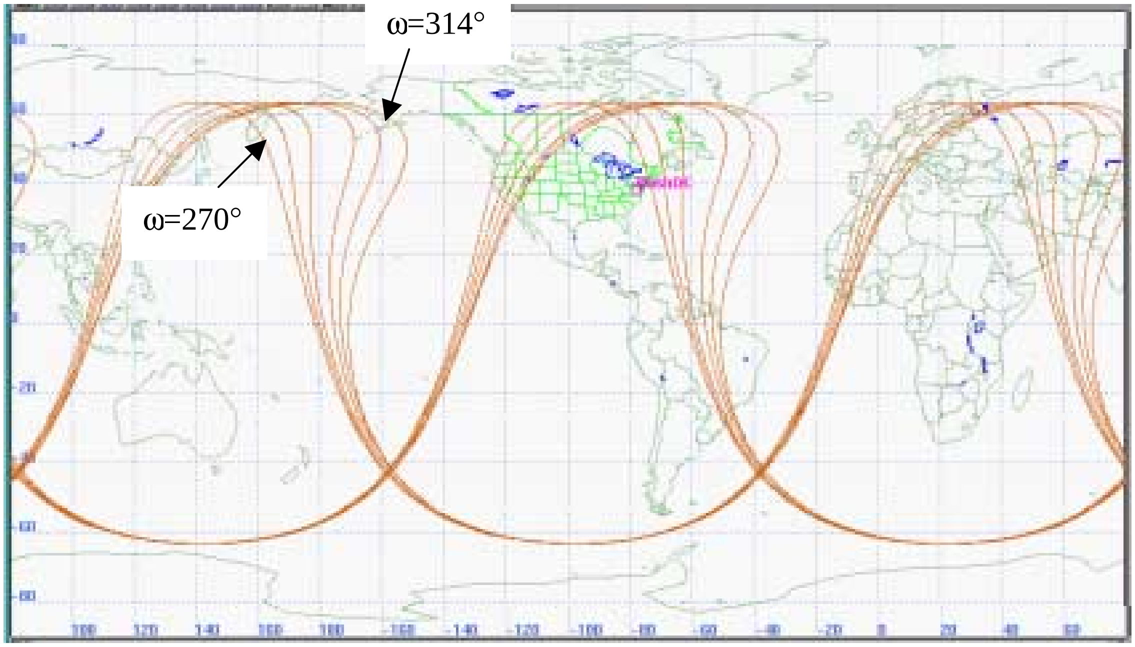

Figure 2
8-Hr Elliptic Ground Tracks with Varying Amounts of "Right Lean"

The 90/270 non-leaning tracks appear to be roughly parabolic and symmetrical about a north-south axis. For other than 90° or 270° arguments of perigee, the ground traces have a noticeable lean, or tilt, either to the right or to the left. Figure 1 shows several 8-hr ground tracks with varying amounts of 'left lean', depending on the argument of perigee selected. Figure 2 shows a similar plot for right leaning ground tracks. The further the excursion from 270° (or 90°), the more the lean. In point of fact, the authors of this paper have studied elliptical orbits with 'maximum lean' (i.e., with both apogee and perigee lying in the Equatorial plane- equivalent to arguments of perigee of 0° or 180°).[16]

One other important characteristic that satellite constellation designers employ is the repeating ground track. These orbits, when viewed from an earth oriented frame of reference, have nadir points tracking over the same path with some selected repeat cycle. Normally this repeat cycle is selected to be one day, or an integral number of days, although other repeat cycles can be used.[17]

A Basic COBRA Array

A six-satellite array using 8-hour left-leaning (or right-leaning) elliptic orbits is capable of continuously covering virtually all the Northern Hemisphere. In Fig. 3, all six satellites are placed in a single, left-leaning, repeating ground track. We refer to this arrangement as a basic COBRA array. Since there are three complete cycles (orbits) per day, there are three 'loops' in the ground track. Apogees are all in the Northern Hemisphere, where the orbital velocities are lower and more closely match the earth's rotational velocity. For this reason, the Northern Hemisphere loops are narrower than they are in the Southern Hemisphere, where the velocities are much higher with satellites traversing a wider range of longitude in less time. The three distinct loops, as well as the three apogee (and three perigee) locations all lie exactly 120 degrees apart in longitude, as one would expect. A right-leaning six-satellite COBRA array is shown in Figure 4. In the left-leaning loops (Fig. 3), the satellites at 15°N have a mean anomaly of 90°, while those at 60°N have an MA of 270°. This situation is just reversed for the right-leaning loops (Fig. 4).

A single satellite in a leaning eight-hour elliptic orbit should be considered as a basic building block having a number of desirable characteristics. One is that the ground trace of the active arc is oriented more in the north-south direction, roughly along a meridian of longitude. We can select any preferred meridian (or meridian trio), by adjusting the right ascension of the orbit. In this manner, the basic COBRA orbit (and by extension the basic COBRA multiple satellite arrays), yields a number of advantages for tailoring coverage of selected latitudes or geographical areas. By contrast, a non-leaning elliptic orbit has a more east-west orientation for the active arc that provides no such flexibility for selecting coverage areas. Moreover, we have no control over the parallel of latitude in which these non-leaning satellites congregate; this is constrained to a range at or near 63.4 degrees of latitude- which happens to be the critical inclination for elliptic orbit line-of-apsides stability.

Although the basic COBRA array provides continuous Northern Hemisphere coverage, it is evident that at the changeover points, where a 270° MA satellite goes silent and an oncoming 90° MA satellite becomes active (see Fig. 3), ground antennas would be required to shift position suddenly (or 'slew') approximately 45° to maintain communications. During this slewing period a brief interruption of communications might be expected, particularly for mechanically oriented antennas. One way around this problem is to use phased array antennas. Another approach (but not too economical) is to use multiple antennas. Also, there are electronic methods for handling such handoffs involving buffering or memory storage.

Payload Duty Cycles in Elliptic Orbits

It is important to recognize that in most elliptic constellations, the satellites are not continuously active. Rather, they are predominantly most useful at the higher altitudes at, and on either side of, their apogees. Here, they have larger footprints, and appear to move very slowly. When viewing a computer simulation of multiple prograde elliptic orbit satellites in a common ground track, they do in fact move more slowly

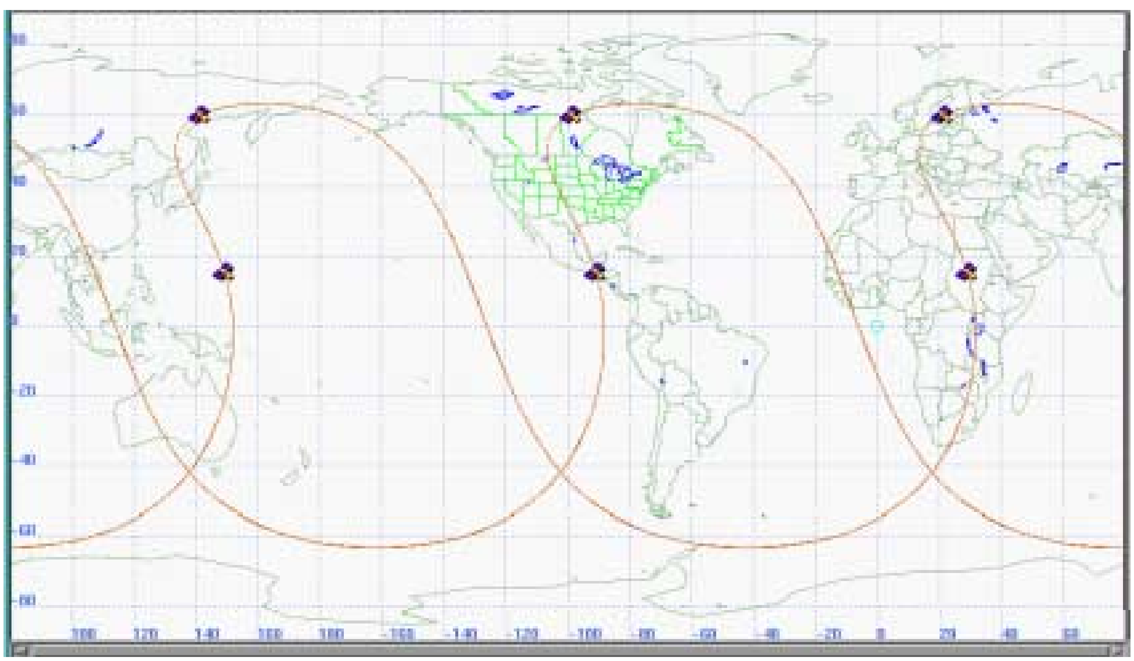

Fig. 3 Left Leaning COBRA Track with Six Satellites
(Satellites at 15°N are at Start of Active Arc. Those at 60°N are at End of Active Arc)

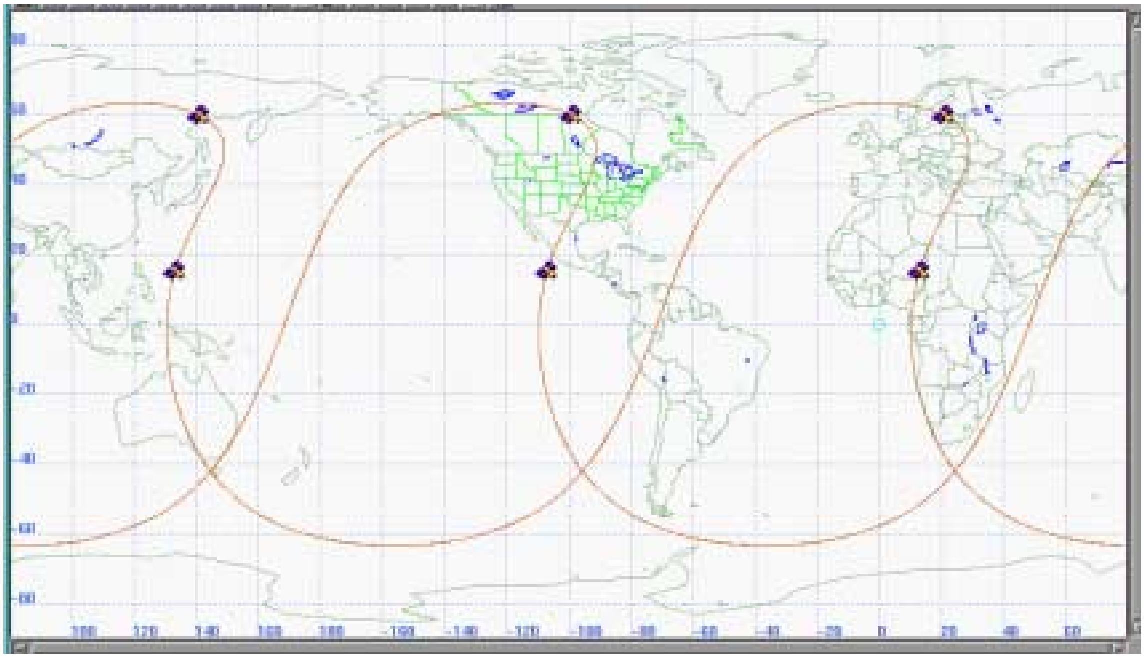

Fig. 4 Right Leaning COBRA Track with Six Satellites
(Satellites at 60°N are at start of active arc; those at 15°N are at end of active arc)

at and near apogee, and thus tend to 'bunch together'. Conversely, while they are passing through other portions of the track, at or on either side of the perigee locations, they will tend to move much more rapidly, and their in-track spacing will be much greater. In these regions, the payload is turned off, but the solar arrays can still generate electrical power for storage in the satellites' batteries.

In the basic COBRA six-satellite array, the satellites' communications payloads are active along the short arcs between 15 and 60 degrees of North latitude in Figures 3 and 4. Each of these short arcs represents exactly one-half of an orbital period. In terms of mean anomaly, these active arcs lie between 90° and 270° MA. Since this translates into exactly one-half of the orbital period, the payload duty cycle is thus 50%. The

TABLE I
ORBITAL ELEMENTS
ELLIPTICAL (COBRA), BASIC ARRAY, LEFT-LEANING
[A BASIC SIX SATELLITE CONSTELLATION PROVIDING CONTINUOUS CLOSED PATH ANTENNA TRACKING IN EACH OF THREE GEOGRAPHICAL REGIONS]

SAT #	a (km)	e	i (deg)	RAAN (deg)	ω (deg)	M(deg)
1	20261	0.6458	63.41	60	226.45	90
2	20261	0.6458	63.41	180	226.45	90
3	20261	0.6458	63.41	300	226.45	90
4	20261	0.6458	63.41	0	226.45	270
5	20261	0.6458	63.41	120	226.45	270
6	20261	0.6458	63.41	240	226.45	270

Table II
ORBITAL CHARACTERISTICS
ELLIPTICAL (COBRA), BASIC ARRAY, LEFT-LEANING
[A BASIC SIX SATELLITE CONSTELLATION PROVIDING CONTINUOUS HIGH ELEVATION COVERAGE IN THREE NORTHERN HEMISPHERE GEOGRAPHICAL REGIONS]

Apogee Alt (km)	Perigee Alt. (km)	Apogee Lats, All (deg)	Perigee Lats, All (deg)
26978	807	40.5N	40.5S

Apogee Long$_1$ (deg)	Apogee Long$_2$ (deg)	Apogee Long$_3$ (deg)
103.7W	16.3E	136.3E

Perigee Long$_1$ (deg)	Perigee Long$_2$ (deg)	Perigee Long$_3$ (deg)
103.4W	16.6E	136.6E

Start of Active Arcs Lat (deg)	End of Active Arcs Lat (deg)
15.5°N	60.0°N

Start Long$_1$ (deg)	Start Long$_2$ (deg)	Start Long$_3$ (deg)
100.0W	20.0E	140.0E

End Long$_1$ (deg)	End Long$_2$ (deg)	End Long$_3$ (deg)
110.6W	9.4E	129.4E

shape of these active arcs suggested a coiled snake and actually led to calling them "COBRA" arcs. Later, working backwards from this acronym, the expanded name "Communications Orbiting Broadband Repeating Array" was coined to fit the acronym initials. The orbital elements for the basic six-satellite left-leaning COBRA array are given in Table I. A number of key orbital characteristics involving apogee, perigee and crossover data are presented in Table II.

The SRA COBRA "Teardrop" Array

The invention of the Teardrop concept retained the good features of the basic COBRA, and in addition removed the necessity for ground antennas to slew in position during the changeover, or transition. Basically, a left-leaning COBRA track containing three satellites is combined with a right-leaning COBRA track that also contains three satellites. These satellite triplets are time-phased, for each teardrop, to meet at two crossover points in space. The resultant effect is to create an inverted (in the Northern Hemisphere) teardrop-shaped trace. To a mid-latitude observer on the ground in or near the teardrop it then appears that one active satellite is continuously circling nearly overhead. It should be noted that this closed path is only possible because the left-leaning COBRA active arcs go from South to North, while the right-leaning arcs travel in the reverse direction – from North to South! Since the original, basic COBRA active arcs started and ended on a different meridian of longitude, it was necessary to make adjustments so that all of the COBRA Teardrop arcs would begin and end on the same longitude. After doing this, it was relatively easy to join the end points of the active arcs. Of course, exactly joining the end points of the left-leaning and right-leaning active arcs, would lead to a series of unacceptable in-space satellite collisions. We calculated that offsetting the tracks by 15-20 km would avoid the collision problem, while not affecting tracking by ground based antennas. Figure 5 shows a six-satellite basic Teardrop array, with the active arcs highlighted.

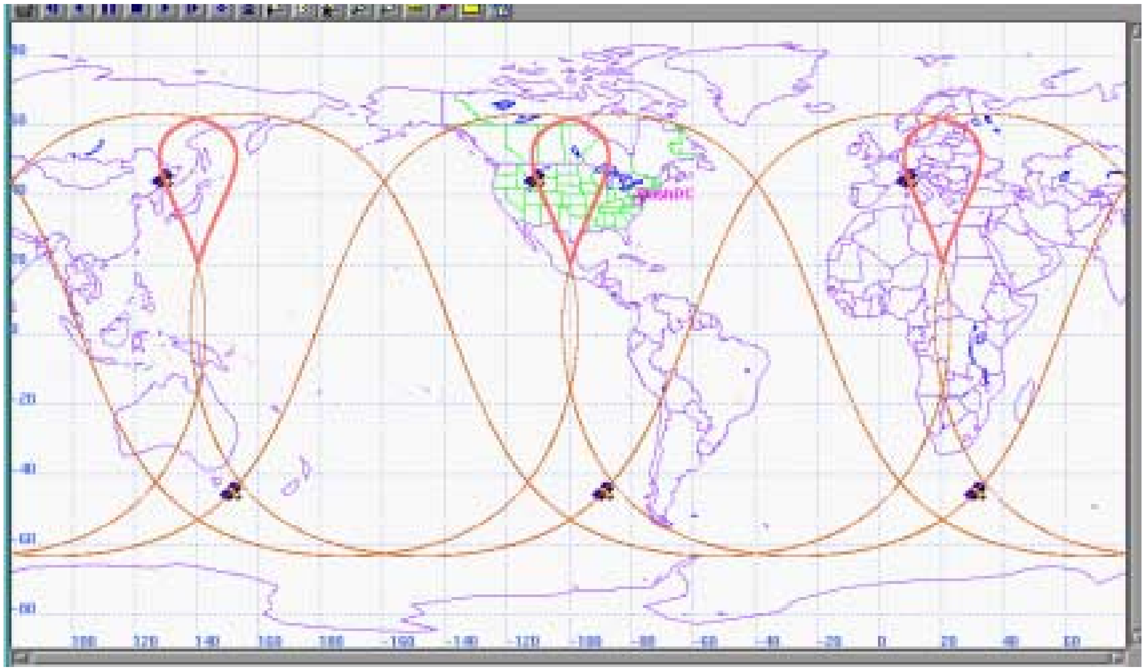

Fig. 5
Basic 6-Satellite Teardrop Array. Left-Leaning Satellites at Apogees; Right-Leaning Satellites at Perigees

We have found that up to twelve teardrops can be constructed in the Northern Hemisphere (and twelve in the Southern Hemisphere) while maintaining a 2° angular separation between teardrops to prevent electronic interference. See Figure 6. If satellites are spaced 2° in-track in a COBRA Teardrop, as many as 24 active satellites can be accommodated in each Teardrop. See Figure 7. But, in order to maintain this teardrop coverage continuously requires the other two teardrops in Figure 5 to be populated as well, giving 72 active NH positions. With the 50% duty cycle, these three Teardrops would then contain a total of 144 satellites (including the inactive satellites). If all 24 teardrops in both hemispheres were populated to the maximum extent, there would be 576 active positions, provided by a grand total of 1152 satellites.

The orbital elements for a basic six-satellite COBRA Teardrop are given in Table III, with various Teardrop orbital characteristics in Table IV.

TABLE III
ORBITAL ELEMENTS
ELLIPTICAL (COBRA) TEARDROP ARRAY
[A BASIC SIX SATELLITE CONSTELLATION PROVIDING CONTINUOUS CLOSED PATH ANTENNA TRACKING IN EACH OF THREE GEOGRAPHICAL REGIONS]

SAT #	a (km)	e	i (deg)	RAAN (deg)	ω (deg)	M(deg)
1	20261	0.6458	63.41	138.5	232	180
2	20261	0.6458	63.41	18.5	232	180
3	20261	0.6458	63.41	258.5	232	180
4	20261	0.6458	63.41	100.2	308	0
5	20261	0.6458	63.41	340.2	308	0
6	20261	0.6458	63.41	220.2	308	0

Table IV
ORBITAL CHARACTERISTICS
ELLIPTICAL (COBRA) TEARDROP ARRAY
[A BASIC SIX SATELLITE CONSTELLATION PROVIDING CONTINUOUS CLOSED PATH ANTENNA TRACKING IN EACH OF THREE GEOGRAPHICAL REGIONS]

Apogee Alt (km)	**Perigee Alt. (km)**	**Crossover Alt, All (km)**
26978	**798**	**20730**
Apogee Latitudes, All (deg)	**Crossover Lat$_S$ (deg)**	**Crossover Lat$_N$ (deg)**
44.9N	**20.4N**	**62.2N**
Crossover Long$_1$ (deg)	**Crossover Long$_2$ (deg)**	**Crossover Long$_3$ (deg)**
100W	**20E**	**140E**
Apogee Long$_1$ (deg)*	**Apogee Long$_2$ (deg)***	**Apogee Long$_3$ (deg)***
110.6W	**9.4E**	**129.4E**
Apogee Long$_4$ (deg)**	**Apogee Long$_5$ (deg)****	**Apogee Long$_6$ (deg)****
89.4W	**30.6E**	**150.6E**

*** Left-Leaning Active Arcs**
**** Right-Leaning Active Arcs**

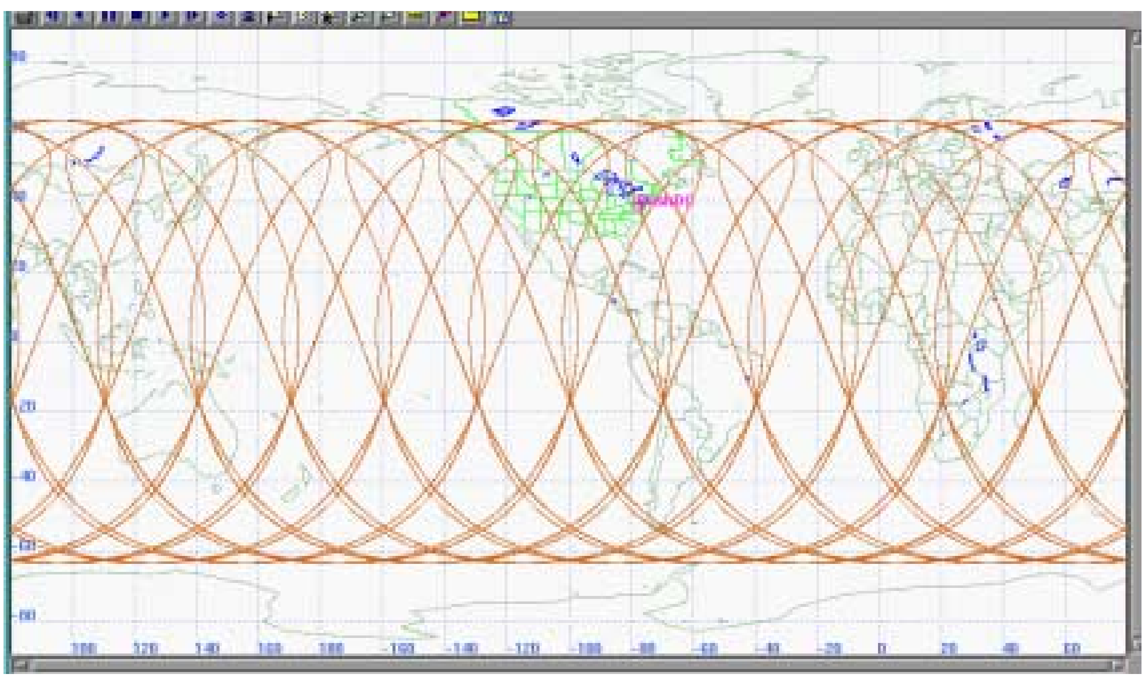

Fig. 6
Diagram Showing 12 Northern Hemisphere Teardrops. (This is the Maximum Number Possible While Maintaining at Least Two Degrees Separation between Adjacent Teardrops)

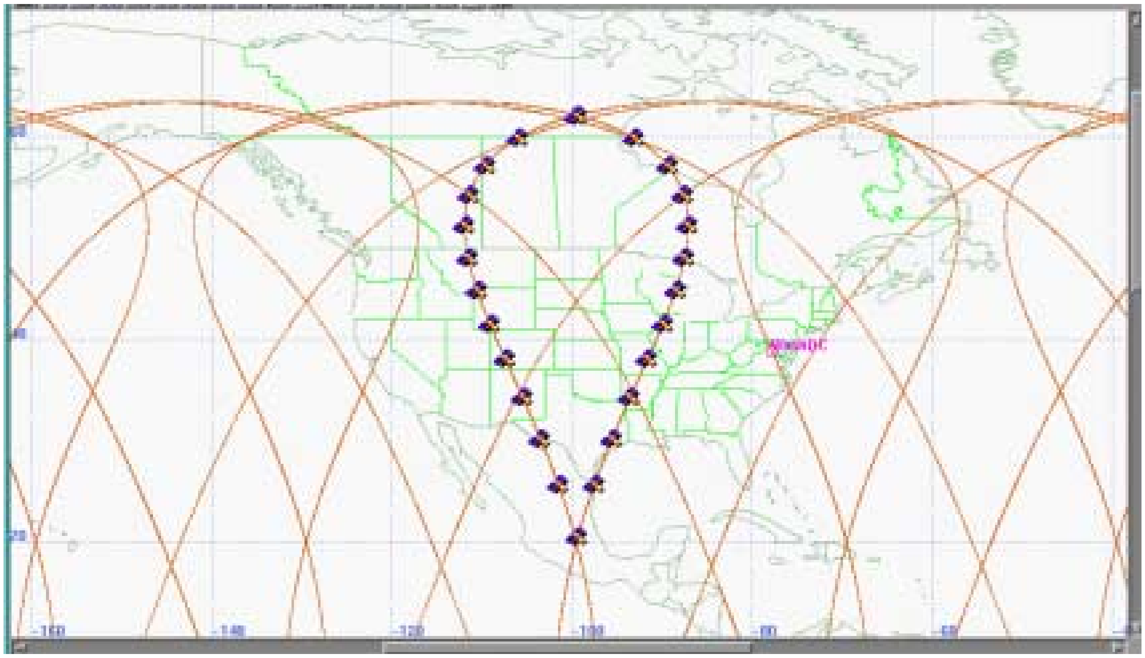

Fig. 7
Snapshot of Single Teardrop Showing Twenty-Four Active Satellites
With a Minimum 2° In-Track Separation

Coverage Characteristics:

The footprints of the basic COBRA and COBRA Teardrop satellites are quite large, due to their relatively high operating altitudes (21,000 to 27,000 km). Typically, the footprints for both the active arcs in a Teardrop array centered on the US extend well down into South America, for low to medium elevation angles (5-10 degrees). See Figures 8 and 9. The minimum elevation angles for such a Teardrop for observers at all locations within the continental US are actually in excess of 50°, with average elevation angles even higher.

Advantages of 'Teardrops':

A major advantage of the Teardrop system is that it takes considerably less energy (smaller launch vehicles) to launch into an 8-hour elliptical orbit, than into a 24-hour GEO orbit. It is fairly well known that the apogee kick impulse required to circularize a GEO orbit requires approximately the same mass of fuel as mass in the satellite itself. Since the GEO transfer orbit is approximately a 12-hour elliptical orbit, it should be obvious that a given booster should be able to launch considerably more than twice as much satellite mass into a final Teardrop orbit, as into a GEO orbit.

The operating altitude range of the satellites is about two-thirds that of the GEO satellites. This means lower link margins, lower latency or time delay, and lower requirements on transmitted power.

The effects of radiation have not yet been studied in detail for the 8-hour elliptic COBRA orbits. However, studies on a 3-hour sun-synchronous orbit have been conducted. These showed considerably lower radiation levels exist for these leaning elliptical orbits than for the non-leaning versions. This lessening of radiation occurs because both the apogees and perigees are closer to the Equatorial plane in these leaning orbits. The perigee altitudes are mostly below the Van Allen belt, while the apogees are above this belt in Equatorial latitudes. In the mid-altitude range, the satellites are generally at mid- to high-latitudes, where the radiation levels are much lower.

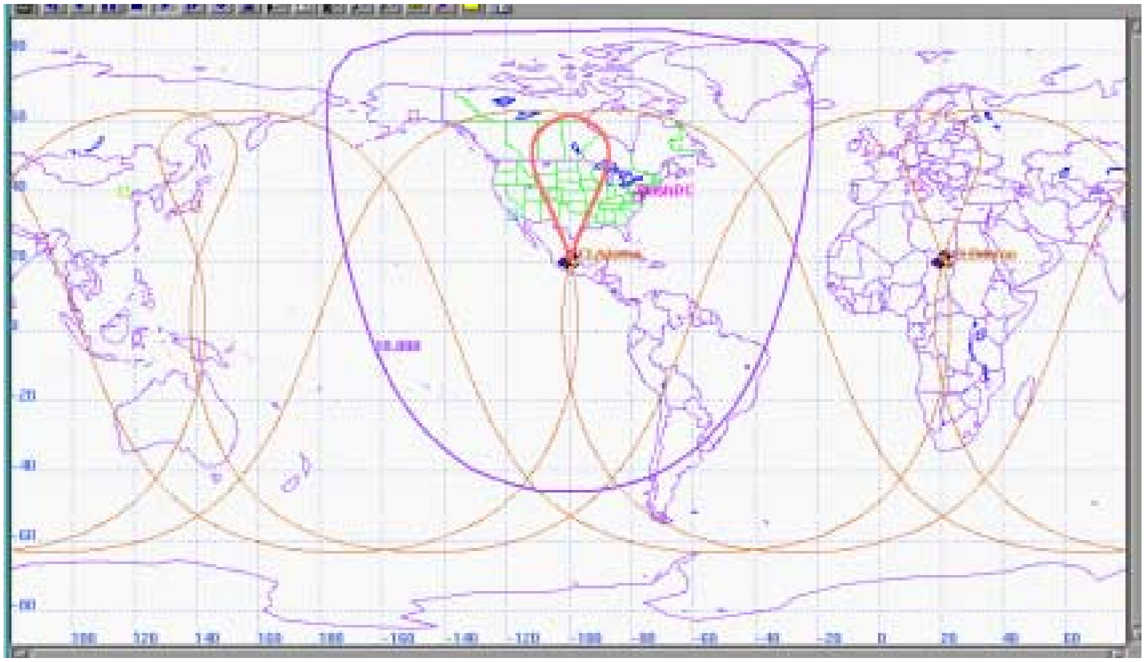

Fig. 8
Snapshot of US Teardrop Demo with One Satellite at Southern Crossover Point over North America and the Other Satellite at Southern Crossover Point of European Teardrop. (10° Elevation Angle Contour Line Shown)

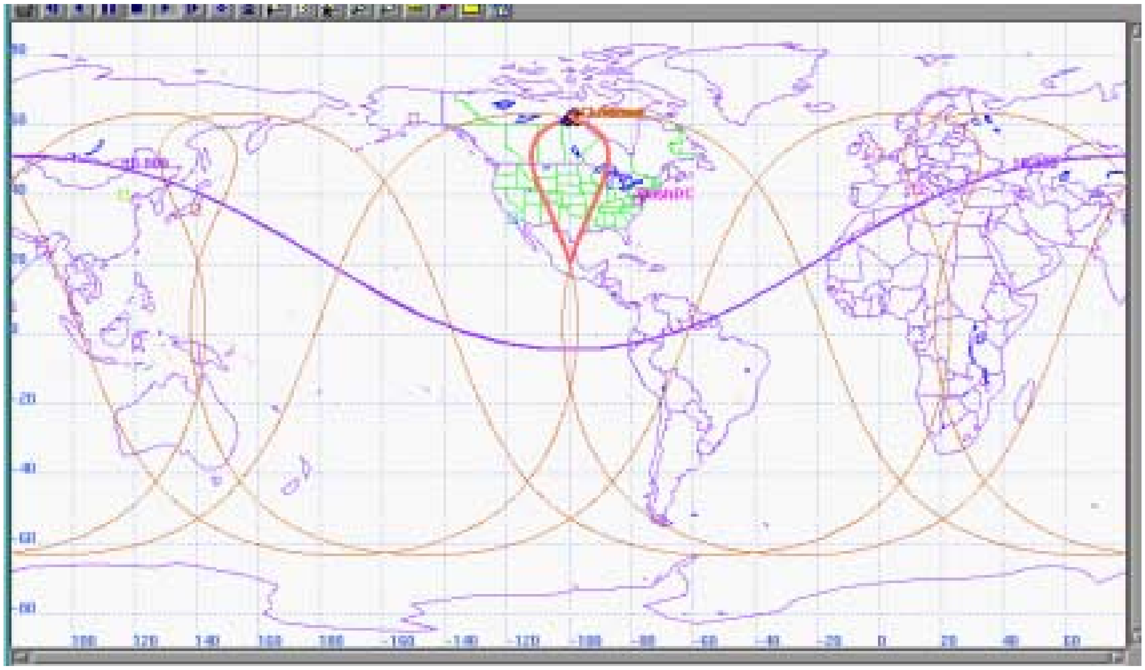

Fig. 9
Snapshot of US Teardrop Demo with Both Satellites at Northern Crossover Point over North America with minimum of 15-20 km separation to avoid collision
(10° Elevation Angle Contour Line Shown)

The high elevation angles typical of both basic COBRA and COBRA Teardrop facilitate the use of higher frequencies for two-way satellite communications. This is because the satellites are looking almost straight down at the earth, resulting in minimum signal attenuation. The attenuation due to rain, or severe weather is roughly proportional to the cosecant of the elevation angle; thus satellites at 90° elevation angles would have much less attenuation (-3 db) than satellites seen from the ground at a 30° elevation angle.[18]

Probably the only disadvantage with an elliptical orbit is the changing altitude. This is not too difficult to handle, however, if the range of altitudes in the active arcs is not too great, as is the case with COBRA.

Two-Satellite SmallSat Demo:

In order to demonstrate all aspects of the Basic COBRA and the COBRA Teardrop systems, Space Resource America is planning to orbit two smallsats with minimal broadband capable communications payloads. The demonstration will result, among other things, in eight hours of continuous access for each of three regional Northern Hemisphere regions separated by 120° of longitude. Moreover, these eight hour access blocks will occur at the same local time of day in each of the three periods.

Some of the goals of the two-satellite COBRA Teardrop demonstration are:

1. Demonstrate a variety of broadband applications, using Ku or Ka band frequencies. Include both fixed and mobile ground terminals of opportunity.
2. Demonstrate the orbital stability of the system with minimum station-keeping ΔV. For COBRA Teardrop demonstrate a consistent "miss distance" between satellites at the crossover points.
3. Demonstrate lack of interference with Geostationary satellites (active satellites will be visible in a different part of the sky).
4. Demonstrate the angular in-track and cross-track COBRA satellite separations that can be accommodated by various ground antennas with two satellites operating at the same frequency in close proximity.
5. Demonstrate successful handoffs at the satellite crossover points for COBRA Teardrop.
6. Demonstrate successful ground antenna slewing and seamless transition from starting points of COBRA active arcs to end points (Note: slewing not required for closed path COBRA Teardrops).
7. Demonstrate the minimum acceptable miss distance between satellites at the teardrop crossover points. The proposed 15-20 km minimum distance may be reduced once sufficient operational experience with the teardrop demo has been accumulated.

Projected Applications:

The previously discussed advantages of the COBRA Teardrop arrays (high elevation angles at mid and high latitudes, closed path space trajectory requiring no slewing of antennas to new positions) open up a wide range of possible applications for their use. Some of these will be discussed in this section.

1. Broadcast Radio/TV. The use of a Teardrop constellation for this type of application would be in direct competition with existing GEO systems such as DirecTV (in the case of broadcast TV), as well as the 24-hour elliptical Sirius and 24-hour GEO XM broadcast radio systems being introduced this year. It should be noted that these geosynchronous systems are somewhat limited in the longitudinal area covered- they are intended to cover a region not more than 120° wide in longitude centered on the meridian location of the GEO satellite. By contrast, the Teardrop array would cover the entire Northern hemisphere, with each satellite sequentially serving different geographic areas. Thus, the same satellite would alternately be providing service to North America, then to Asia, and finally on to Europe. The control of the satellites' commercial payloads and service content would be passed from region to region matching the coverage area being served until all three regions were covered. One single regional service provider could thus lease, or own, a maximum of one-third the total capacity of the entire Northern Hemisphere system. However, if several broadcast providers were to share the satellites' capacity in one particular region, they each would then only be using a fraction of one-third of the total Teardrop system capacity. A significant market for broadcast applications should be found

among mobile terminals (ships, aircraft, automobiles, etc.)

2. Broadband Point to Multipoint. This application is aimed at the broad objective of “Internet in the Sky”. It could serve users ubiquitously, especially in sparsely populated areas where fiber nets are non-existent due to cost considerations.
3. Air Traffic Control with Flight Parameter Monitoring. The Teardrop arrays would appear to be ideally suited to commercial and business aviation requirements. They provide high angle of elevation satellites, and continuous coverage even in the polar regions where GEO satellites cannot reach. In utilizing their capacity for high data rate transmission, they could provide continuous transmission of in-flight data and voice to an air route traffic center. To date, this type of information has been transcribed on the cockpit voice recorders (CVRs) and flight data recorders (FDRs) in order to reconstruct the circumstances around aircraft accidents. Unfortunately, these devices go down with the aircraft, and sometimes are lost or so severely damaged that no information can be extracted from them. The continuing transmission with immediate availability in the event of an accident would greatly improve the search and rescue capabilities (by providing GPS location of the crash site) as well as an immediate indication of the cause(s) of the accident. The data accumulated at the ground collection site could be erased upon successful completion of the aircraft’s flight, to avoid overload of data collection.
4. Military Theater Communications. The use of a series of Teardrop arrays could provide entire global coverage for military tactical and strategic communications requirements. Some or all of the channels, whether voice or data, could be encrypted as needed. The use of higher frequencies and higher data rates is facilitated by the high elevation angles possible. High elevation also implies low probability of intercept (LPI).
5. Maritime (commercial & military). Ships could satisfy most of their communications needs using Teardrop arrays centered on mid-ocean longitude meridians. Higher elevation angles result in less signal attenuation; this may become very important under stormy conditions, when most maritime emergencies can be expected to occur.
6. Meteorological. Fitted with the proper sensors, views looking straight down at cloud formations, eyes of hurricanes, etc., are continuously possible even at higher latitudes.
7. Navigational. Surprisingly, the Teardrop orbits are actually more stable than either GEO or LEO orbits. Being subjected to less perturbing forces, their paths will be more predictable. They could provide useful supplements to GPS or Galileo navigation systems.
8. HDR Trunking. Using Intersatellite Links (ISLs), complete and continuous one hop hemispheric interconnectivity can be realized between all three active satellites in a basic Teardrop system. Thus, a station in the US could transmit to the North American active arc satellite, which would select the ISL to either the Asian or European Teardrop for subsequent downlinking to their respective markets.

Conclusions

Basic COBRA and COBRA Teardrop arrays have a number of significant advantages over the presently congested GEO satellites ring circling the earth at the Equator. Among these are:

- **Non-interference with GEO systems:** The design of the basic COBRA (and the COBRA Teardrop) orbit eliminates any electronic interference between these satellites and any satellite in the GEO ring. When in the active duty cycle, all COBRA satellites lie above a plane that passes through the North Pole (or below a similar plane passing through the South Pole for SH COBRAs). Thus, any observer on the earth would find the COBRA satellites in a different portion of the sky than the GEO satellites occupy with 10-15 degrees of angular separation.
- **Non-interference within a single (or multiple) COBRA Teardrop system(s):** Up to 576 slowly moving positions that will maintain a minimum 2° separation from each other can be supported in a global Teardrop system (having twelve Teardrops in each of the Northern and Southern Hemispheres).

- **<u>Higher minimum and average elevation angles than GEOs in the mid to high latitudes:</u>** In the mid to high latitude regions (including the polar regions), minimum elevation angles of 50° or more can be achieved. Average elevation angles will be even higher. Polar triple coverage is always assured, since all three Teardrop patterns will be continuously visible at high Northern (or Southern) latitudes.
- **<u>Cost Effectiveness:</u>** Although more COBRA satellites will be required for hemispheric coverage, the satellites will be somewhat smaller, and will require much less ΔV to orbit. Thus the cost for their launch vehicles will be significantly decreased. Furthermore, less signal attenuation due to the higher elevation angles leads to an appreciable reduction in EIRP requirements, and a further reduction in satellite launch mass.
- **<u>Ease of De-Orbit:</u>** De-orbiting spent COBRA satellites requires only a small amount of de-orbit fuel, for a retro impulse at apogee. This reduces the perigee altitude to a point where atmospheric drag ensures the rapid de-orbit, and destruction, of the satellite. In this way, no orbital debris is left in orbit, as is the case with both GEO and MEO systems.
- **<u>Graceful Degradation:</u>** In the event of failure of a single satellite in a basic COBRA or a COBRA Teardrop system, the effects on loss of coverage in each region is minimized. For a six-satellite basic system, for example, each regional area will experience only four hours of outage per day until the satellite is replaced.

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