



Circular vs. Elliptical Orbits for Persistent Communications

James R. Wertz
Microcosm, Inc.



5th Responsive Space Conference
April 23–26, 2007
Los Angeles, CA

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Abstract

Responsive Communications missions typically require “persistent communications,” i.e., repeat coverage that lasts for an extended period or the entire day. LEO orbits cannot provide this coverage without a large number of satellites and GEO satellites are typically large and expensive, with a long development time. The solution has traditionally been thought of as moderate altitude elliptical orbits, such as Magic or Cobra orbits. However, recent IR&D work by Microcosm suggests that this may be the wrong answer. This paper compares moderate altitude elliptical and circular orbits in terms of coverage, coverage flexibility, constellation size, ASAT vulnerability, the environment, impact on spacecraft design, and overall system cost. The conclusion reached is that circular MEO orbits are a better choice than elliptical MEO orbits for supplementary or persistent communications.

Background

One of the key missions for Responsive Space is persistent supplemental communications. There is an ever-increasing demand for both voice and high bandwidth data communications in military applications. This is an area with high potential for responsive systems because the need and location of the demand may change rapidly with the changing world situation. Properly designed, low-cost, responsive communications systems could greatly alleviate this problem.

The traditional choices have been either large geosynchronous (GEO) communications satellites, such as MilStar, or low Earth orbit (LEO) communications constellations, such as Iridium. The GEO systems tend to be very expensive and high power with development and deployment schedules that can run a decade or more.

LEO systems also tend to be expensive because of the large number of satellites required for global coverage. In addition, LEO global communications systems have had major financial problems in the past. The Iridium constellation of 66 satellites was built at a cost of approximately \$5.5 billion and ultimately sold for \$25 million.

For responsive supplemental communications, we want focused coverage of a particular region that can be put in place rapidly and at low cost. 24/7 coverage would be best, but intermittent coverage could also have significant utility. The goal is to trade away global coverage and long life for dramatically reduced cost and launch-on-demand.

At RS3 Microcosm presented a paper that, based on our work and others, recommended the potential use of an elliptical (Magic) orbit for supplemental persistent communications [Hopkins, undated; Wertz, 2005]. The general characteristics of the Magic orbit are as follows:

- Elliptical orbit with a 3 hour period (525 km x 7,800 km orbit).
- Critical inclination of 63.4 deg or 116.6 deg.
- Argument of perigee adjusted so that apogee covers the latitude of interest.
- Provides approximately 1 hour of coverage once/day or possibly twice/day.
- Constellation of 12 to 24 satellites required to provide 24/7 coverage, although full coverage may be available in some cases with smaller numbers of satellites.

A possible alternative to the Magic orbit is a medium Earth orbit (MEO) constellation using circular orbits at an altitude of 5,000 to 15,000 km. The purpose of this paper is to compare the MEO circular orbit constellation with the Magic

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[†]Microcosm, Inc., 4940 West 147th Street, Hawthorne, CA 90250-6708.

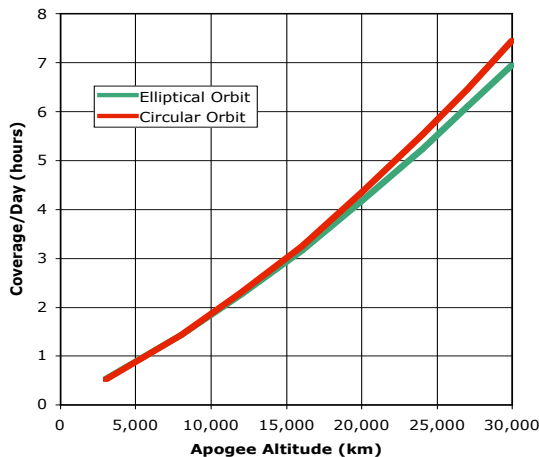
Email: jwertz@smad.com

orbit constellation in terms of the key parameters that determine system cost, performance, and vulnerability.

Coverage

Perhaps the most fundamental characteristic of importance to persistent communications is the coverage per satellite, shown in Fig. 1 for both elliptical and circular orbits. We compare orbits with the same apogee altitude (rather than mean altitude) because the Magic orbit system is intended to do most of its communications at or near apogee and it is this altitude that sizes the communication and power systems. In addition, by comparing them at the same apogee altitude, the power and antenna size for the ground system will be the same.

Fig. 1. Coverage vs. Apogee Altitude for Circular and Elliptical Orbits. See text for discussion.

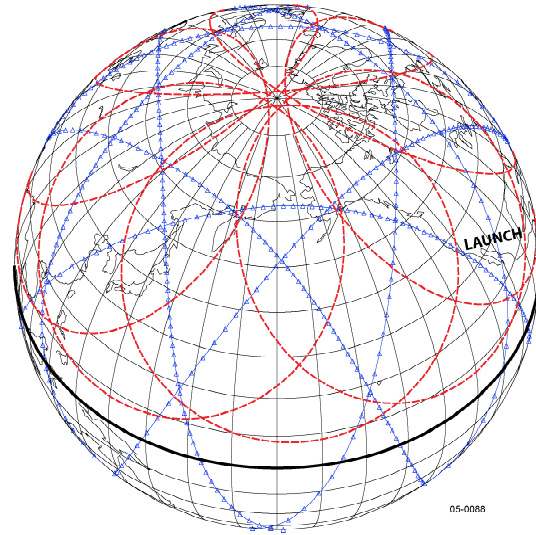


The results in Figure 1 seem counterintuitive. For two satellites at the same altitude, one in a circular orbit and one at apogee of an elliptical orbit, the elliptical orbit satellite will be traveling slower and, therefore, would appear to be in view of the ground for a longer period. However, the elliptical orbit drops quickly toward perigee and the satellite soon disappears from view. In the circular orbit, the satellite remains at a high altitude and, therefore, can be seen over a longer arc.

Persistent communications requires both good coverage per satellite and an appropriate constellation pattern. A typical ground track

pattern and coverage for the Magic orbit is shown in Fig. 2. Because the spacecraft do not remain fixed relative to each other, cross links will require a significant steering range.

Fig. 2. Ground Track (blue) and coverage circles (red) for a Magic orbit.



With the MEO circular orbit constellation, we create a “street of coverage” pattern in which multiple satellites in a single plane provide a band of coverage around the world centered on the orbit plane. (See, for example, Wertz [2001].) In this pattern, satellites remain fixed with respect to each other over time, such that cross links require only fine steering to take into account attitude motion or the small variations due to higher order orbit perturbations.

A traditional MEO circular orbit pattern is shown in Fig. 3A. This pattern requires up to 3 cross-links to get data 180 deg around the world. Above 7,000 km altitude, an alternative interlocking pattern is available as shown in Fig. 3B. In this case, the same 6 satellites provide a redundant constellation and a single cross link can get data 180 deg around the world. This reduces the amount of hardware that is tied up in any individual data transmission and, therefore, increases by a factor of 2 to 3 the effective data throughput available for a given set of hardware. The coverage circles for a 6-satellite constellation at 10,000 km altitude are shown in Fig. 4. Note that the overlap will increase substantially as the altitude is increased or the effective working elevation angle is decreased.

Fig. 3. A (top) Traditional “Street-of-Coverage” Pattern. B (bottom) Interlocking Pattern Available above 7,000 km.

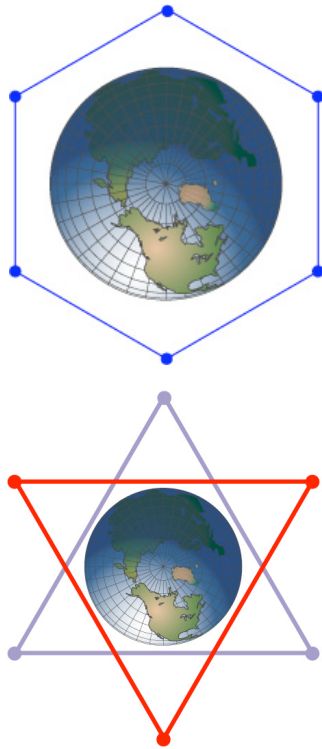
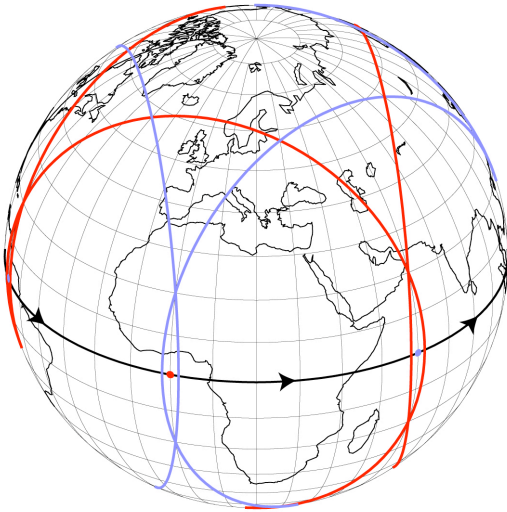


Fig. 4. Coverage Circles for an Interlocking Pattern Equatorial Constellation at 10,000 km altitude.



Depending on the altitude and minimum working angle, the MEO circular orbit constellation can provide a very wide swath or coverage band

centered on the orbit plane. Table 1 gives typical values for the swath width for varying altitudes and numbers of satellites. Depending on the latitude, we can provide continuous coverage with 4 to 6 satellites at 8,000 km and 3 to 5 satellites at 15,000 km. Under essentially all circumstances, the circular orbit constellation provides better coverage (i.e., uses fewer satellites and covers a larger area) than an elliptical orbit constellation with the same apogee.

Table 1. Swath Width as a Function of Altitude and Number of Satellites for a MEO circular orbit “Street-of-Coverage” pattern. The values given assume a 10 deg minimum working elevation angle.

Altitude	# of Sats	Swath Width
5,000 km	6	74.7 deg
5,000 km	5	63.4 deg
5,000 km	4	26.4 deg
8,000 km	6	94.5 deg
8,000 km	5	86.8 deg
8,000 km	4	67.5 deg
15,000 km	5	111.5 deg
15,000 km	4	99.8 deg
15,000 km	3	48.8 deg

Vulnerability

The recent Chinese ASAT test clearly demonstrates the vulnerability of low altitude satellites. The intercept of a satellite in LEO requires a launch delta V of somewhat more than 3,500 m/s which can be provided by a single stage, suborbital vehicle. A LEO communications or surveillance satellite has to fly over the area of interest and, therefore, is a potential target. An intercept can occur in approximately 5 to 8 minutes.

One of the best defenses against ASAT weapons is altitude. A satellite in MEO does not need to fly over the target area and can communicate with mid-latitude regions from over the equator (or over the poles). An intercept in MEO can take 20 to 30 minutes, which may be sufficient time to maneuver or deploy a decoy or chaff.

Reaching MEO altitudes requires a launch delta V in excess of 12,000 m/s, which is more delta V than is required to put a satellite into LEO and requires a 3-stage or very high performance 2-stage launch vehicle. If the satellite is over the equator, then the ASAT launch must be moved to the vicinity of the equator or an even longer time and higher delta V will be required. Thus, while the MEO altitudes do not provide complete safety, they are much less vulnerable to ASATs than LEO satellites.

The elliptical Magic orbit is intermediate in vulnerability between the LEO and MEO orbits. It generally flies over the area of interest near apogee at high altitudes. It will be at vulnerable LEO altitudes over much of the orbit, but not necessarily when it is over the target area. Unfortunately, if the satellite is, for example, at apogee over the target area on an ascending pass, then 12 hours later on a descending pass over the target, the satellite will be at a much lower altitude, typically at or near perigee. Thus, depending on the specific conditions of the target/satellite geometry, it is likely that Magic orbit will have much of the same vulnerability as the LEO orbit.

Orbit Flexibility and Accessibility

The elliptical Magic orbit must be at the critical inclination of 63.4 deg or its complement of 116.6 deg in order to avoid the rapid rotation of perigee due to the Earth's oblateness. (See, for example, Wertz [2001] or Vallado [2001].) Within this orbit plane, apogee can be maintained over any desired orientation around the orbit so as to provide good coverage at varying latitudes. However, this does provide a potential failure mode if the critical inclination is not achieved.

In contrast, for the circular MEO constellation both the altitude and inclination are essentially "free parameters" that can be adjusted as needed to meet the needs of a particular mission. In general, the specific values achieved will not be critical. Thus, the circular orbit eliminates the potential failure mode and provides more flexibility in meeting specific coverage objectives.

In addition, there are two special cases of interest in the circular MEO orbits.

- **Equatorial Ring.** A single ring of satellites around the equator provides continuous coverage for all latitudes that fall within the width of the Street-of-Coverage band defined in Table 1. Depending on the number of satellites, altitude, and minimum working elevation angle, this can provide continuous coverage for latitudes as far north and south as 50 deg to 60 deg.
- **Polar Ring.** Similarly, a single ring of satellites in a polar orbit can provide continuous coverage for latitudes within as much as 50 deg to 60 deg of the pole.

Both of the above rings have the added advantage of particularly simple cross-links since the relative positions of the satellites do not change as they move in their orbit. A polar ring plus an equatorial ring could provide whole Earth coverage, although the cross linking between the two rings would be more complex because of their relative motion.

The *accessibility* of an orbit is the mass available in that orbit relative to the mass available in a 100 NMi circular orbit at an inclination equal to the latitude of the launch site. (For a more extended discussion of accessibility, including numerical techniques for evaluating it, see the *Orbit Cost Function* discussion by Wertz [2001].) The actual mass available in any orbit will depend on the launch vehicle, the launch site, and the flight profile. However, if we assume a generic launch capability of 1000 lbs to 100 NMi due east from KSC, then the approximate masses to the orbits of interest are:

- | | |
|---------------------------------------|---------|
| • Magic orbit | 426 lbs |
| • MEO circular,
20 deg inclination | 326 lbs |
| • MEO circular,
70 deg inclination | 249 lbs |

Thus, depending on the latitude of interest, the Magic orbit will allow a somewhat heavier satellite than the MEO circular orbit at an altitude equal to apogee of the Magic orbit.

Radiation Environment and Spacecraft Complexity

For both the Magic and MEO circular orbits the radiation environment is challenging. This is the

primary reason that more MEO constellations are not flying at present.

In low Earth orbit, below approximately 900 km, the radiation environment is relatively benign. However, at the inner edge of the Van Allen belts the radiation environment rises dramatically. (See, for example, Tribble [2003] or Wertz and Larson [1999].) Therefore, both the elliptical Magic orbit and the circular MEO orbits will be in a very high radiation environment, although it may be possible to put the MEO constellation between the proton and electron belts to mitigate the environment problem to some degree. Nonetheless, the fundamental trade for achieving persistent communications is whether the reduced number of satellites and better coverage of the elliptical and MEO orbits is worth the high cost of radiation hardening the satellites. In this respect the elliptical and MEO circular orbits will be very similar. It may be that the shorter expected life for responsive missions will be a key factor in this regard.

The other major system-level trade is on the size and complexity of the spacecraft bus and payload. The geometrical parameters that effect these trades are summarized in Table 2. In LEO a communications spacecraft can be small and simple. However, a single satellite is never in view of one location on the ground for more than 10 to 14 minutes, depending on the altitude and minimum working elevation angle. This, in turn implies the need for a large number of satellites and potentially very high cost.

Table 2. Geometrical Parameters for the Orbits being considered. Assumes a 10 deg minimum working elevation angle. (For computations, see Wertz [2001].)

Parameter	LEO	Magic	Units
Altitude	800	525 x 7,800	km
Range to Horizon	2,370	1,750 – 11,600	km
Earth Ang. Radius	62.7	67.5 – 26.7	deg
Orbit Ang. Vel.	3.8	1.0 – 4.4	deg/min
Ang. Vel. at Nadir	0.53	0.03 – 0.96	deg/sec
	Low MEO	High MEO	
Altitude	8,000	15,000	km
Range to Horizon	11,800	19,300	km
Earth Ang. Radius	26.3	17.4	deg
Orbit Ang. Vel.	1.3	0.7	deg/min
Ang. Vel. at Nadir	0.04	0.02	deg/sec

In many respects the MEO circular constellation is similar to the LEO case. The angular size of the Earth, range to nadir, power requirements, and angular rates are all constant.

In contrast, as can be seen in the table, elliptical orbits cover a wide range in terms of angular size of the Earth, range to nadir (and to the horizon), power requirements, and angular rates. All of these will tend to complicate the design of the payload and spacecraft bus. This problem is mitigated to a degree because the payload does not have to operate in the vicinity of perigee. However, the more the operating range is confined to a region near apogee, the less coverage that is available per satellite. Thus, substantial additional complexity is introduced by using elliptical, rather than circular, orbits.

Conclusion

The overall conclusions for the various aspects of the comparison between elliptical Magic and circular MEO orbits are summarized in Table 3.

Table 3. Conclusions of the Magic vs. MEO Circular Orbit Trade. See text for discussion.

Characteristic	Elliptical (Magic) Orbit	MEO Circular Orbit
Coverage/Satellite	Similar	Similar
Constellation Size	12 - 24 satellites (may be less in some cases)	3 - 6 satellites
ASAT Vulnerability	Moderate – High	Low
Satellite Design Complexity	Complex	Simple
Radiation Environment	High	High (may be able to reduce)
Coverage Flexibility	Moderate (inc. fixed)	High (inc. and altitude variable)
Accessibility	Moderate	Moderate (somewhat less payload mass than Magic orbit with same apogee)
Overall System Cost	Moderate	Low-Moderate

For a given launch vehicle, somewhat more mass is available in the Magic orbit than in the comparable MEO orbit. However, essentially all other aspects of the trades favor the MEO circular

orbits over the Magic elliptical orbits for persistent communications. This is counter to the “traditional” solution of elliptical orbits as previously proposed by Microcosm and others. The preferred orbits for any particular mission may well depend on a detailed design analysis. However, we strongly recommend evaluating constellations of satellites in MEO circular orbits as the likely preferred choice for Persistent Communications.

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