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3rd Responsive Space Conference
April 25–28, 2005
Los Angeles, CA

COVERAGE, RESPONSIVENESS, AND ACCESSIBILITY FOR VARIOUS "RESPONSIVE ORBITS"[*]

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ABSTRACT

We have evaluated 5 potential Responsive Orbits with the following conclusions with respect to coverage, responsiveness, payload to orbit for a small launch vehicle, and missions that they would be best suited for:

- ***Cobra Orbits*** provide up to 4 hours of continuous access per day, 10 hours mean response time, low payload mass to orbit, very poor optical resolution, and are best used for communications.
- ***Magic Orbits*** provide up to 1 hour of continuous access per day, 12 hours mean response time, low to moderate payload mass to orbit, poor optical resolution, and are also best for communications.
- ***LEO Sun Synchronous Orbits*** provide 5 minutes of coverage once or twice per day, 6 hour mean response time, moderate payload mass to orbit, excellent optical resolution, and are best suited for visual or radar observations.
- ***LEO Fast Access Orbits*** provide 5 minutes of coverage once or twice per day, 45 minute mean response time, moderate to high payload mass to orbit, excellent optical resolution, and are best suited for highly responsive visual or radar observations.
- ***LEO Repeat Coverage Orbits*** provide 5 minutes of coverage every 90 minutes for 4 or 5 times in a row, 9 hour mean response time, high payload mass to orbit, excellent optical resolution, and are best suited for repeated visual or radar observations.

Responsive orbits have the potential to provide means for communications and high-resolution surveillance anywhere in the world within hours of an identified demand. Collectively, these orbits provide excellent opportunities for transforming space from a strategic to a tactical asset and for doing missions that cannot now be done. Coupled with the launch vehicles being developed under the AF/DARPA/NASA FALCON program and emerging smallsat technology, there is excellent potential for new, low-cost missions that can transform the way space is used.

OBJECTIVES

The goal of the paper is threefold: (1) to compare and contrast the orbit options typically considered for responsive missions, (2) to look at the characteristics of these orbits in terms of mission needs and potential mission utility, and (3) to determine the launch requirements to achieve these objectives or, equivalently, the typical payload size one could expect from a given class of launch vehicle.

Among the orbits most frequently considered for Responsive Missions are the following:

- Cobra elliptical orbit
- Magic orbit
- LEO Sun synchronous orbit
- LEO Fast Access orbit
- LEO Repeat Coverage orbit

As one would expect, each orbit has advantages and disadvantages in terms of coverage, accessibility, and responsiveness. We evaluate each of these orbit types in terms of the following parameters:

- **Coverage**. Frequency and duration and how that coverage evolves over time (i.e., a few weeks or months).
- **Responsiveness.** Given reasonable constraints on applied delta V, how rapidly can a satellite be launched, put into the desired orbit, and return useful data.
- **Accessibility.** Addressed in terms of the Orbit Cost Function (OCF), which is an approximate measure of the mass that can be put into the desired orbit relative to the mass that can be launched to 100 NMi due east from the launch site.
- **Range to Target.** Maximum and minimum range to target and corresponding resolution of a given optical surveillance instrument.

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- **Environmental Characteristics.** Radiation environment, propellant requirements, and other characteristics that will impact orbit utility.

INTRODUCTION TO RESPONSIVE ORBITS

Responsive Orbits are those intended to meet the needs of responsive missions. The most important characteristics of these orbits are:

- **Responsiveness** — Data returned within a few hours of launch
- **Low Cost** — Reasonable payload available from a small launch vehicle
- **Good Coverage** — Mixture of speed, persistence, and repetitiveness is key
- **Tactical Applications** — Provide data for a specific, defined location on Earth

Long-term stability and global coverage are not principal issues, as they are for more traditional missions. Traditional Earth observation orbits — such as GEO, Molniya, or high altitude Sun synchronous orbits — don't work well for responsive missions. However, the use of non-traditional orbits will inevitably impact the launch system, spacecraft, communications, and operations used for responsive missions. Consequently an assessment of the principal characteristics of these orbits is key to understanding responsive missions. We begin by setting out the defining parameters and coverage characteristics of the 5 most likely responsive orbits.

Cobra Orbit

The Cobra orbit was introduced by John Draim to provide efficient communications for mid-latitude regions [Draim, 2001, 2002]. Properly phased, it can provide coverage that is optimized for latitude, longitude, and time of day when most telephone calls occur. The Cobra orbit is highly elliptical (800 km by 27,000 km) and at the critical inclination of 63.4 deg. Thus, apogee and perigee don't rotate and the pattern is stable over a long term.

The orbit period is 8 hours, and there are 3 orbits per day. As shown in Fig. 1, the Cobra orbit provides approximately 4 hours of continuous coverage near apogee over 3 selected mid-latitude regions that are approximately 120 deg apart in longitude. Thus, a constellation of 6 satellites can provide 24-hour continuous coverage over 3 regions.

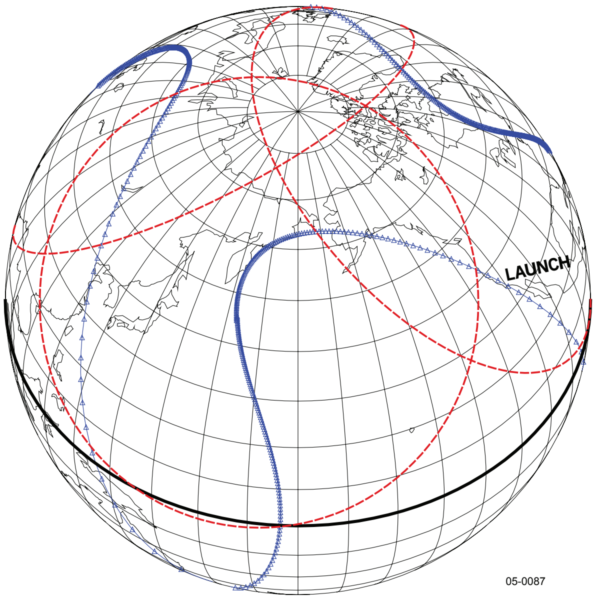

Fig. 1. The Cobra Orbit Provides 4 Hours of Continuous Coverage Over 3 Regions 120 Deg Apart in Longitude.

During most of the coverage period, the satellite is near apogee and, therefore, the average working altitude is approximately 27,000 km. This implies that the resolution of an 0.5 m telescope working in the visible would be about 66 m. Consequently, the principal applications are most likely communications or possibly weather.

Magic Orbit

The Magic orbit has been developed largely by the Aerospace Corp. to provide persistent coverage of regions of interest [Hopkins]. It is also a critically inclined (inclination = 63.4 deg) elliptical orbit with significantly smaller eccentricity than the Cobra orbit. With perigee at 525 km and apogee at 7,800 km, it has a 3-hour period with 8 orbits per day. Both prograde and retrograde Magic orbits are possible. In both cases, they provide approximately 1 hour of continuous coverage over 8 regions of the world 45 deg apart in longitude. (See Fig. 2.) A constellation of 24 satellites would be required for truly continuous coverage, although the substantial overlap means that configurations for specific applications may be able to provide near-continuous coverage with substantially fewer satellites.

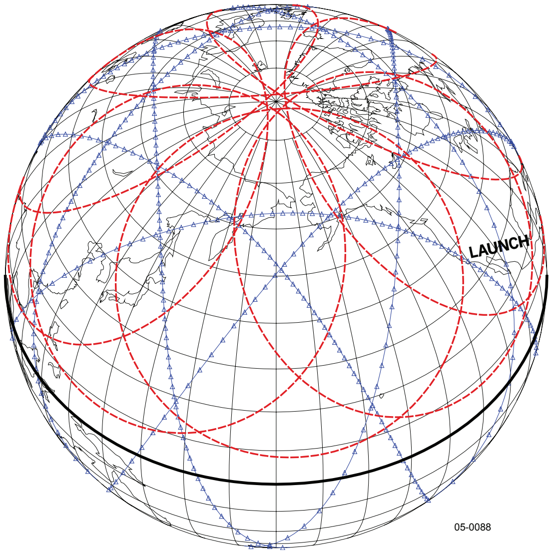

Fig. 2. The Magic Orbit Provides 1 Hour of Continuous Coverage Over 8 Regions 45 Deg Apart in Longitude.

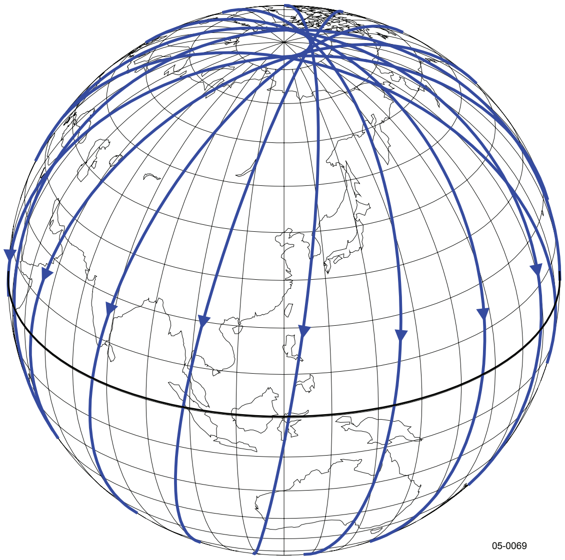

Fig. 3. The LEO Sun Synchronous Orbit (SSO) Provides 5 Minutes of Coverage Once or Twice per Day.

As with the Cobra orbit, the coverage region is centered around apogee and, therefore, the average working altitude will be approximately 7,800 km. The resolution of an 0.5 m telescope working in the visible would be about 19 m. Again, like the Cobra orbit, the principal applications are most likely to be communications or weather, although some surveillance activity could be possible.

LEO Sun Synchronous Orbit (SSO)

The LEO Sun Synchronous Orbit (SSO) is a traditional orbit used for Earth observations. However, in traditional Sun synchronous missions, the orbit will be circular at 700 to 900 km. Because drag is less of an issue for short duration responsive missions, the altitude may be reduced to 300 km or lower. Because of the requirements for Sun synchronous orbits, this implies an inclination closer to 90 deg than for traditional SSO missions, i.e., an inclination of 96.7 deg for a 300 km altitude Responsive SSO. (See for example, Vallado [2001] or Wertz [2000, 2001]).

The SSO maintains approximately the same Sun angle indefinitely. It provides about 5 minutes of coverage twice daily, for example, at 9:00 am and 9:00 pm local time. (See Fig. 3.) Typically, the SSO is designed for global coverage and doesn't have unique characteristics appropriate to responsive missions, except that a reasonable payload can be orbited by a small launch vehicle. Assuming an altitude of 300 km, the resolution of an 0.5 m instrument working in the visible region of the spectrum will be about 0.7 m. Consequently, SSO would be applicable for visible or radar observations.

LEO Fast Access Orbit (FAO)

The LEO Fast Access Orbit (FAO) has been suggested by Microcosm to provide very rapid initial response. Specifically, the spacecraft is launched into an orbit that flies over the target on the first revolution. The ground trace is similar to that of an ICBM, except that the satellite is in an orbit, rather than a trajectory that intersects the Earth. The FAO provides coverage of the target within 90 minutes after launch and once or twice per day thereafter for any identified location on Earth.

Figure 4 illustrates several key aspects of the Fast Access Orbit. For any given launch site, one can define an FAO that goes over any target location on Earth. There would be two possible orbits for each launch site/target combination — one prograde and one retrograde. In practice, range restrictions at nearly all launch sites restrict the available inclinations, due largely to overflight of populated areas or large land masses. In principle this could be overcome by launching, for example, from the middle of the Atlantic Ocean, but the time required to fly to the launch location would make the orbit response time several times longer. (See discussion of Response Time in the next section.) However, most launch sites have a large azimuth range potentially available, such that the whole world could be covered. Fig. 5A shows launches from the Kwajalein Atoll in the southern Pacific that could cover the whole world with prograde Fast Access Orbits. Fig. 5B shows primarily retrograde launches from Vandenberg AFB, covering the entire world.

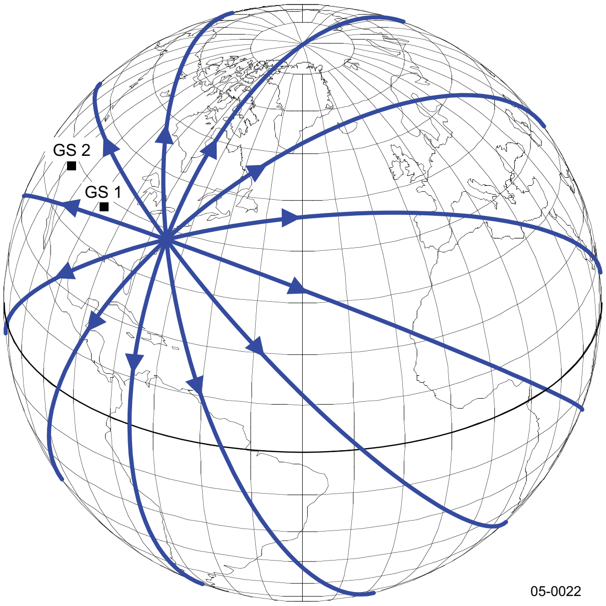

Fig. 4. The LEO Fast Access Orbit (FAO) Provides 3 to 5 Minutes of Coverage within 90 Minutes After Launch and Once or Twice per Day Thereafter for Any Identified Location on Earth.

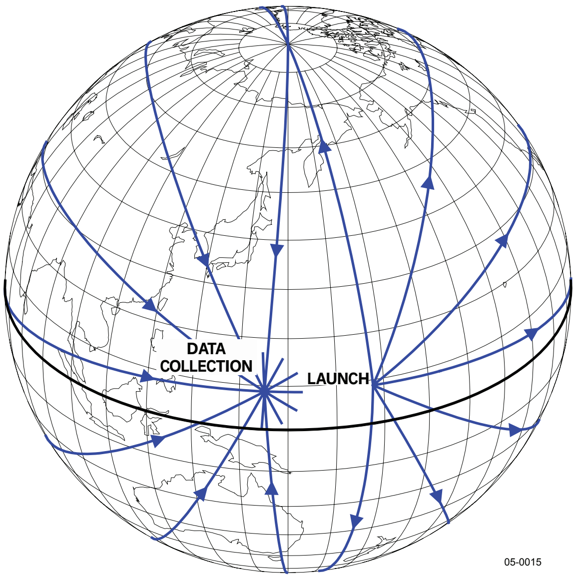

Fig. 5A. Prograde Fast Access Orbits Launched from Kwajalein Atoll in the Marshall Islands.

Responsive orbits are intended specifically to return data within hours of an unanticipated demand, such as an unanticipated natural or man-made disaster. For example, a responsive mission would have been appropriate to search for debris fields immediately after the tsunami that hit southeast Asia in December, 2004. This was an unanticipated event in an unexpected location. While we may be able to launch a satellite in response to this event, we may not have a ground station in the vicinity of the event where data can be downloaded. This problem has a potential resolution with Fast Access Orbits. As can be seen in Figs. 5A and 5B, each of the various FAOs returns to a common location after one orbit, i.e., approximately 90 minutes after launch. Because the satellite is launched into inertial space, it will return to its original location in inertial space after 1 orbit, after 2 orbits, and so on. On the surface of the Earth, this location will be at the same latitude and west of the launch site by about 22.5 deg for each revolution after launch. On Fig. 4, these potential ground station locations are marked as GS1 and GS2 for locations that can receive data from any FAO satellite launched from Wallops Island after 1 orbit and after 2 orbits. Thus, while geosynchronous cross links tend to be both expensive and heavy, and when there may not be a ground station available, a third option exists to recover data after 1 orbit 22.5 deg west of the launch site.

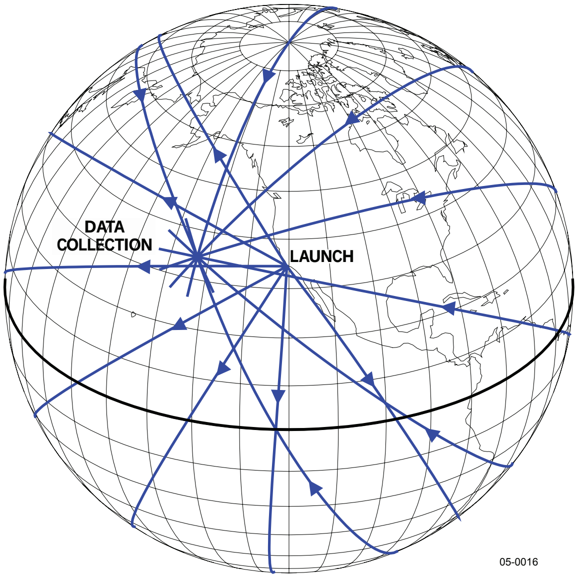

Fig. 5B. Retrograde Fast Access Orbits Launched from Vandenberg AFB, CA.

Like the SSO responsive orbit, we assume a working altitude for the FAO of 300 km. (This could be higher or lower depending on the particular application.) This implies a ground resolution of 0.7 m at nadir for an 0.5 m diameter instrument working in the visible region of the spectrum. Thus, the Fast Access Orbit would be a particularly good choice for visible or radar observations. Because the data is returned very soon after launch, it is also possible to launch the satellite specifically timed to take advantage of weather in the vicinity of the target. Thus, launch could be delayed if required to allow for a forthcoming break in cloud cover over the target.

LEO Repeat Coverage Orbit (RCO)

The LEO Repeat Coverage Orbit (RCO) has been suggested by Microcosm as a potential responsive orbit intended to provide persistent periodic surveillance of an identified Earth target. The spacecraft is launched into an orbit with an inclination 3 to 5 deg higher than the latitude of the target. As shown in Fig. 6, this provides 3 to 5 minutes of coverage per orbit for 4 or 5 successive orbits, i.e., 6 to 8 hours. If additional surveillance is needed, a constellation of 3 or 4 satellites could provide coverage every 90 minutes indefinitely, and 6 or 8 satellites could provide coverage every 45 minutes indefinitely. The later satellites in the constellation could be launched after the results of the initial surveillance showed that additional coverage was appropriate.

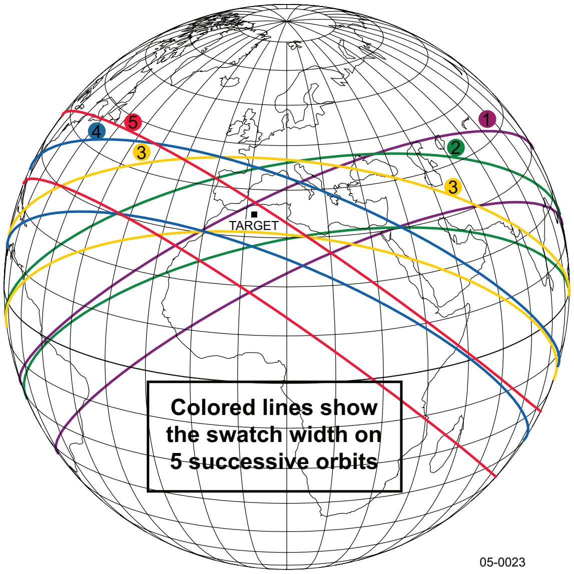

Fig. 6. The LEO Repeat Coverage Orbit (RCO) Provides 3 to 5 Minutes of Coverage per Orbit for 4 or 5 Successive Orbits (i.e., 6 to 8 hours).

As with the other low altitude responsive orbits, we assume a circular orbit at 300 km. Again, this provides a resolution of 0.7 m at nadir for an 0.5 m diameter instrument working in the visible. Thus, this would be particularly appropriate for visible or radar observations or IR or low-light visible sensors, if observations at night were also critical.

RESPONSIVENESS

Of course, the key characteristic of Responsive Orbits is that they are responsive — that is, data is returned to the user within a small number of hours of a previously unanticipated demand. Generally, we can think of responsiveness in either of two ways. In circumstances of military conflict or civil unrest, there may be a level of advance warning, such that the system can be put on an alert status and potentially remain there for some time. (There may be several different levels of alert, corresponding for example, to having a crew available, moving the vehicle to the launch pad, or having it fueled and ready to launch within a few minutes.) Alternatively, circumstances such as the southeast Asian tsunami occur basically without warning and launch must be done from a "cold start."

Irrespective of the alert status, we define the ***Response Time*** as the time from an identified demand until the first orbit data is delivered to the end user. The response time will be the sum of 6 different elements that make up the ***Data Response Timeline***:

Response Time = Preparation Time + Weather Delay + Launch Window Delay + Insertion Time + Orbit Response Time + Data Return Time

where:

Preparation Time (PT) = Time from an identified demand to being ready to launch (e.g., 24 hours after alert for the AF/DARPA/NASA FALCON program)

Launch Window Delay (LWD) = Time from being ready to launch until the launch window opens (= when launch site is in the desired inertial orbit plane)

LWD = 0 when the time of day of the observation is not important

LWD = 24 hrs maximum (12 hours mean) when the time of day of the observation is fixed

Weather Delay (WD) = Any additional delay due to being unable to launch due to weather

Insertion Time (IT) = Time from lift-off to arrival in orbit = ~20 min

Orbit Response Time (ORT) = Time from arrival in orbit until the first observation of the target

Data Return Time (DRT) = Time from an observation until data is given to the end user

The Insertion Time is typically small compared to the other elements. The Data Return Time can range from a few minutes to several hours, depending primarily on when and where the observations are downlinked to the ground. The Launch Window Delay is important only when the observation is required to be at a particular time of day. When this is not the case, or when there is broad latitude on the time of day of the observations, then the Response Time is determined primarily by the Preparation Time, the Weather Delay, and the Orbit Response Time, discussed below.

All orbits are approximately fixed in inertial space, although they may move up to 7 deg/day in right ascension (the celestial equivalent of longitude) due to perturbations caused by the oblateness of the Earth. The launch-site-to-target geometry remains fixed because both are rotating with the Earth. Thus, for a given responsive orbit, changing the launch time only changes the time of the day of the target observations. All of the orbits will be essentially Sun synchronous for a few weeks, although over time the Earth's oblateness and other perturbations will cause the time of day of the observations to change. (The amount of this shift for each of the responsive orbits is tabulated in Table 4 in the Conclusions section.)

The fastest way for a spacecraft to get over a target of interest is to fly there at the orbital velocity of approximately Mach 25, just as the fastest way to get an airplane to a target of opportunity is to fly it there. The second fastest approach is to launch the spacecraft into inertial space and allow the rotation of the Earth to bring the target to the spacecraft at about Mach 1.4 at the equator.

Orbit Response Time

Three issues determine the Orbit Response Time (ORT):

- If observations can be made on both the northbound and southbound orbit legs, then there may be two or more observation or communication opportunities per day
- If the orbit goes directly from the launch site to the target (i.e., the Fast Access Orbit) then the ORT will be a fraction of an orbit period (i.e., less than 90 minutes)
- In general for orbits with 1 opportunity period per day, the rotation of the Earth will bring the target under the orbit plane, and the ORT could be as much as 24 hours for a target just east of the initial groundtrack

Except for the Fast Access Orbit, the ORT will depend primarily on the relative geometry between the launch site and the target. After launch, the spacecraft orbit plane will be fixed in inertial space. The Earth rotates underneath the orbit plane at 15 deg/hr. Thus, the spacecraft orbit plane, and observation opportunities, will move westward with respect to the surface of the Earth at 15 deg/hr in longitude. Typically, adjustments can be made in the launch profile to ensure that the spacecraft passes over, or nearly over, the target on the first opportunity, rather than have the target fall between two orbit passes.

The Orbit Response Times for the five responsive orbits are given in Table 1 and shown in Fig. 7. For purposes of the tabulation, we have assumed that the LEO Sun synchronous orbit has 2 opportunities/day, and that the Fast Access Orbit is restricted to about 180 deg of launch azimuth, as illustrated in the examples shown in Fig. 5 above.

Orbit	Opportunities /Day	Max. ORT	Mean ORT
Cobra	1	20 hrs	10 hrs
Magic	1	23 hrs	11.5 hrs
LEO Sun Sync	1 or 2*	12 hrs	6 hrs
LEO Fast Access	1 or 2*	1.5 hrs	0.75 hrs
LEO Repeat Cov.	4 to 5	18 hrs	9 hrs

* Depends on target latitude and launch-site-to-target geometry.

Table 1. Opportunities Per Day and Orbit Response Time for Various Responsive Orbits.

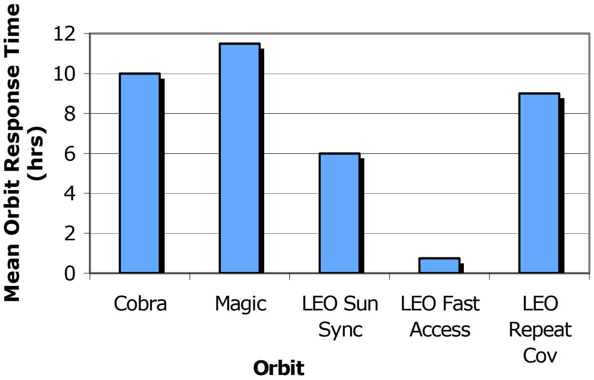

Fig. 7. Mean Orbit Response Time for Various Responsive Orbits.

ACCESSIBILITY

Accessibility refers to the mass available in a given responsive orbit. It is most conveniently measured by the ***Orbit Cost Function*** (OCF), which is the ratio of the mass available in a 100 NMi circular orbit due east from the launch site to that available in the mission orbit. (See Wertz [2000] for an extended discussion of the OCF.) Consequently, 1000/OCF will give the approximate mass in the mission orbit using the AF/DARPA/NASA FALCON launch vehicle because the payload requirement for the program is 1000 lbs to a 100 NMi mile circular, due east orbit. Of course, specific launch vehicles may differ substantially in their payload capability to orbit.

Table 2 and Fig. 8 show the OCF and minimum available payload in various responsive orbits using a launch vehicle that can put 1000 lbs into a 100 NMi LEO circular orbit due east of the launch site. The data assumes that the spacecraft does the final burn (which is substantially more efficient than having the launch vehicle do the final burn), using an I_{sp} of 300 sec. However, the propellant mass (and associated tank mass) required for the burn has been accounted for. That is, the mass shown is the mass of the spacecraft (including payload and remaining propellant) that can be put in the specified orbit. The range of numbers for both the LEO Fast Access and LEO Repeat Coverage orbits reflect the fact that the inclination of these orbits depends on the relative position on the Earth of the launch site and the target. The plot in Fig. 8 shows the worst case inclination, i.e., the one that provides the minimum available mass on orbit.

Orbit	OCF*	Payload (Prograde)	Payload (Retrograde)
Cobra	2.77	360 lbs	
Magic	1.97 – 2.83	509 lbs	353 lbs
LEO Sun Sync	1.54		650 lbs
LEO Fast Access	1.03 – 2.08	692 – 997 lbs**	480 – 692 lbs**
LEO Repeat Cov.	1.03 – 1.45	692 – 997 lbs**	

* Orbit Cost Function

** Depends on both latitude of launch site and target location

Table 2. Orbit Cost Function and Payload Mass in Various Responsive Orbits.

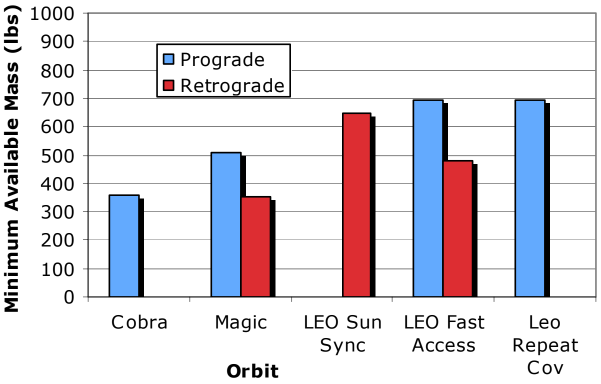

Fig. 8. Minimum Available Mass in Various Responsive Orbits Assuming a Launch Capability of 1000 lbs to a 100 NMi Circular Orbit Due East of the Launch Site

ENVIRONMENTAL FACTORS

Table 3 shows the qualitative effect of radiation and drag on the various responsive orbits. Assuming there is a propulsion system on board the spacecraft for orbit maintenance, environmental effects are not likely to be important for short tactical missions. Thus, even though the radiation environment is harsh for both the Cobra and Magic orbits, it might make sense to provide only a moderate level of radiation protection to keep down the spacecraft mass and cost, on the assumption that the mission will last only a few years or less. Similarly, we have assumed that the LEO responsive orbits are at only 300 km altitude. While this is much lower than typical LEO longer-lived missions, it may well be justified by the desire to get high-resolution imagery with a small instrument. At this altitude, a relatively inexpensive 0.5 m aperture instrument working in the visible will have a resolution at nadir of 0.7 m.

Orbit	Radiation	Drag
Cobra	Very High	Very Low
Magic	Very High	Very Low
LEO Sun Sync	Low	High – Very High
LEO Fast Access	Low	High – Very High
LEO Repeat Coverage	Low	High – Very High

Table 3. Summary of Environmental Effects for Various Responsive Orbits.

SUMMARY

Table 4 provides a summary of the key characteristics of the various responsive orbits that we have evaluated. It also provides a broad framework for evaluating other orbits that may be considered. The most important properties for each of the orbits are shown in bold.

CONCLUSIONS

Responsive missions will likely use more than one orbit type. The most likely orbits are:

- Cobra or Magic orbits for persistent communications (1 to 4 hours of continuous coverage once /day per satellite)
- LEO Fast Access orbit for truly responsive visible, IR, or radar surveillance (0.75 hour mean time from launch to being over the target)
- LEO Repeat Coverage orbit for repeated visible, IR, or radar surveillance [5 minute coverage per orbit for 4 or 5 successive orbits (6 to 8 hours) per satellite per day]

Orbit	**Cobra**	**Magic**	**LEO Sun Sync**	**Leo Fast Access**	**LEO Repeat Coverage**
Introduced By	John Draim	Aerospace Corp	Historical	Microcosm	Microcosm
Key Characteristics	3 revs/day, tear-drop ground track; apogee fixed	8 rev/day repeating grnd track; apogee fixed; may be Sun sync.	Maintains approx same Sun angles indefinitely	Flies over target on first or second orbit	Target coverage on 4 or 5 successive orbits
Orbit Size	800 x 27,000 km	525 x 7,800 km	typ: 300 km circ	typ: 300 km circ	typ: 300 km circ
Inclination	63.4 deg	R: 116.6 deg; P: 63.4 deg	96.7 deg	P: 0 to 90 deg; R: 90 to 180 deg	3-5 deg above lat of interest
Coverage	**~4 hrs once/day**	**~1 hr once/day**	**5 min twice/day, ~12 hrs apart**	5 min once or twice/day, ~ 12 hrs apart	**~5 min per orbit for 4 or 5 successive orbits (6-8 hrs)**
Coverage Evolution	5 min earlier per day	8 min earlier per day	approximately constant	15 to 30 min per day earlier	20 to 30 min per day earlier
Coverage Latitude	Best at mid-lat (40 to 50 deg)	Adjustable between ±65 deg	Global	Global	Global
Coverage Altitude	27,000 km	7,800 km	typical: 300 km	typical: 300 km	typical: 300 km
Orbit Response Time	20 hrs max 10 hrs mean	23 hrs max 11.5 hrs mean	12 hrs max 6 hrs mean	**1.5 hrs max** **0.7 hrs mean**	18 hrs max 9 hrs mean
Launch Window Wait	Max of 12 to 24 hours if specific time of day at target is required. 0 if specific time of day at target is not required.				
Available Mass*	P: 360 lbs	P: 510 lbs R: 350 lbs	R: 650 lbs	P: 680 to 980 lbs R: 480 to 680 lbs	P: 680 to 980 lbs
Radiation	High	Very High	Low	Very Low	Very Low
Drag	Very Low	Low	High to Very High	High to Very High	High to Very High
Resolution**	66 m	19 m	**0.7 m**	**0.7 m**	**0.7 m**
Best Application	**Persistent Communications**	**Persistent Communications**	**Surveillance**	**Responsive Surveillance**	**Repeated Surveillance**

*based on 1000 lbs to 100 NMi dues east from launch site. P=Prograde, R=Retrograde.

** Resolution from apogee at nadir of an 0.5 m diffraction limited instrument operating in visible light.

Table 4. Summary of Key Characteristics of Various Responsive Orbits

Low altitude responsive orbits can provide better than 1 m ground resolution with an 0.5 m aperture instrument at low to moderate cost and weight. Assuming a launch vehicle capability of 1000 lbs to 100 NMi due east (the requirement of the AF/DARPA/NASA FALCON program), the available spacecraft mass in various responsive orbits ranges from 350 to 1000 lbs. The range will typically be 350 to 500 lbs for the communications-oriented elliptical orbits, 700 to 1000 lbs for prograde surveillance orbits, and 500 to 700 lbs for retrograde surveillance orbits.

The mean Orbit Response Time ranges from 0.75 to 12 hours, depending primarily on the orbit chosen. The fastest way to get a spacecraft over the target is to fly it there at the spacecraft velocity of approximately Mach 25. The second fastest approach is to launch the spacecraft into orbit and allow the Earth's rotation to bring the target under the orbit plane at about Mach 1.4 at the equator.

The total response time is driven primarily by preparation time, weather delays, and the orbit response time. Assuming that a launch vehicle can be developed with a short preparation time and all-weather launch, and that the spacecraft, communications, and operations to support the missions are developed, it is reasonable to expect that data can be returned from anywhere in the world within a few hours of a newly identified demand. Responsive space can become a truly tactical asset.

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