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Moderately Elliptical Very Low Orbits (MEVLOs) as a Long-Term Solution to Orbital Debris

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ABSTRACT

Long-term orbital debris is a continually growing problem that has proven challenging to overcome. A straightforward solution to the problem is to put the majority of future LEO spacecraft into *Moderately Elliptical Very Low Orbits (MEVLOs)* with perigees below approximately 300 km, apogees below approximately 500 km, and eccentricities in the range of 0.015 to 0.030. Orbital debris clouds cannot be sustained in this altitude regime and will decay and re-enter in times ranging from a few weeks to at most the time until the next solar maximum. This means that the debris population at this altitude is, and will remain, much lower than at higher altitudes and, of course, any satellites which explode or otherwise die in this region will not be a part of a long-term debris problem. The advantage of the elliptical orbit is that if a temporary failure causes the spacecraft to stop doing orbit maintenance burns for a moderate period of time, apogee will decay, perigee will change very little, and the orbit can be recovered with essentially no loss of total delta V. Of course, if the loss of orbit maintenance delta V is permanent, then the spacecraft will decay and re-enter, as is desirable.

BACKGROUND — ORBITAL DEBRIS AS A CHALLENGING PROBLEM

Long-term orbital debris has been a persistent problem for low-Earth orbit (LEO) spacecraft that was made more critical and more visible by the 2007 Chinese ASAT test and the Iridium 33/Cosmos 2251 collision which left a debris cloud that could remain for as long as 1000 years. [5, 6, 21] Debris can consist of everything from defunct spacecraft to paint chips that break off that can damage payloads and spacecraft subsystems. There are over 19,000 pieces of debris currently being tracked by the Space Surveillance Network (SSN); however, estimates place small debris (<10cm) in the millions. This is debris that is not being tracked, but can still inflict significant damage. Opeila gives an explanation of the makeup of small debris, while Baiocchi and Wesler gives an idea of the large debris currently being tracked.[13, 1] Orbital debris presents an ever growing problem that could endanger the future use of space. This was first discussed in 1978 with the *Kessler syndrome*, where the density of objects in LEO will increase to the point of cascading collisions would render all of space unusable.[7]

The problems associated with orbital debris are now well known. For a current overview of the problem, see, for example Spencer and Madler, Chan, or Liou and Johnson.[17, 2, 8] In somewhat older, but more extensive, treatments Milne provides a general overview of the orbital debris problem, Chan gives an analysis of spacecraft probability of collision, and Smirnov gives a summary of mitigation methods.[11, 2, 15]

As space becomes more populated, the orbital debris problem becomes worse and has led to a great many attempts to find ways to monitor and/or remove orbital debris.[9, 10] While some of these may ultimately be successful, it has become clear that removing large amounts of orbital debris or preventing it from accumulating is, at best, a very expensive and challenging task. However, it is possible to mitigate the problem by the correct orbit selection for future space missions.

THE ATMOSPHERE AND ORBITAL DEBRIS AT LOW SPACECRAFT ALTITUDES

At sea level, the atmosphere is predominantly N_2 and the ambient pressure and density change with local weather, but not in response to the 11-year solar cycle. At satellite altitudes in the vicinity of 800 km, the heating due to space weather causes the atmospheric density to change by a factor of 10 to 100 or more from solar minimum to solar maximum.[25] At this altitude the principal constituent (90%) is monatomic oxygen, O, which is particularly reactive and will generally stick to the spacecraft surface, transferring its momentum to the spacecraft, causing drag, and "weathering" the surface.[16, 4]

As shown in Fig. 1, an altitude of 200 km is an intermediate regime in which the maximum variation over the solar cycle is a factor of 2-4 and 60% of the atmosphere is still N_2.[25, 16] As is the case at higher altitudes, the mean free path of the molecules is much longer than the spacecraft, such that there is no aerodynamics in the sense of an airplane. It is simply a collection of individual interactions between the molecules in the atmosphere and the spacecraft, which is traveling much faster than the molecules. Typically, each molecule will either stick (as O does) and transfer its momentum to the spacecraft or bounce (such as N_2) and transfer twice its momentum to the spacecraft, or less if it hits a slanted surface. It is this continuous set of molecular interactions that causes both drag and aerodynamic torque.

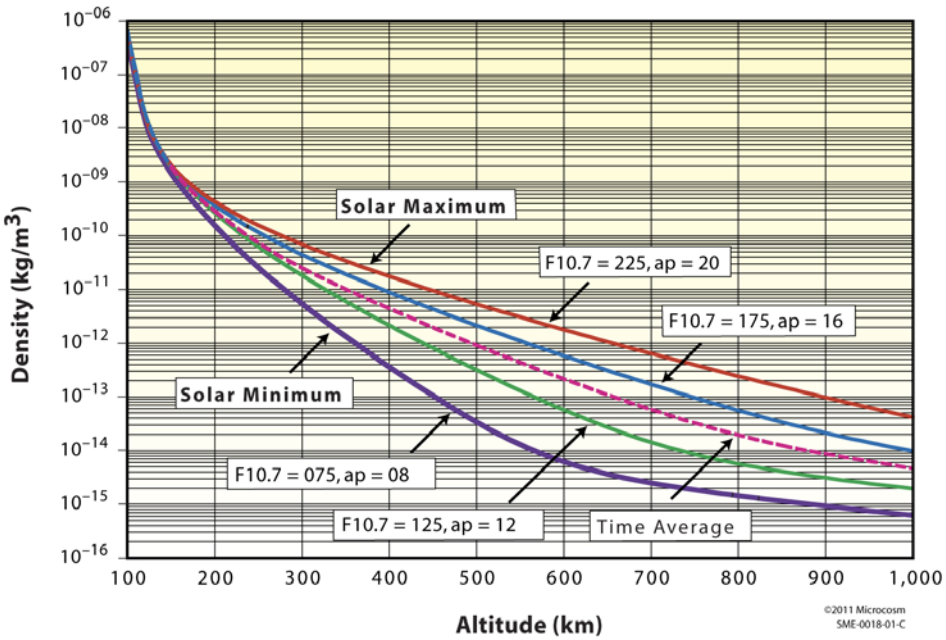

Figure 1: Atmospheric Density in LEO for various values of the F10.7 index. The F10.7 index is a measure of solar activity. (from Wertz.[25])

The orbital debris distribution at LEO altitudes is shown in Fig. 2. At altitudes below approximately 500 km, the debris density is about an order of magnitude lower than at altitudes of 700 to 1000 km. The key issue here is that Fig. 2 is, in some respects, the inverse of Fig. 1. At altitudes below approximately 500 km, the atmospheric density is high and, because of that, the debris density is low. As illustrated in the next section, objects in this altitude regime decay and re-enter the atmosphere in a short period of time. While the debris from the Iridium 33/Cosmos 2251 collision, which occurred at 790 km, may last for 1000 years or so, a similar collision at 300 to 400 km would create a debris cloud that would last for only a few months. At these altitudes, the atmosphere becomes a natural vacuum cleaner and removes orbital debris effectively and quickly.

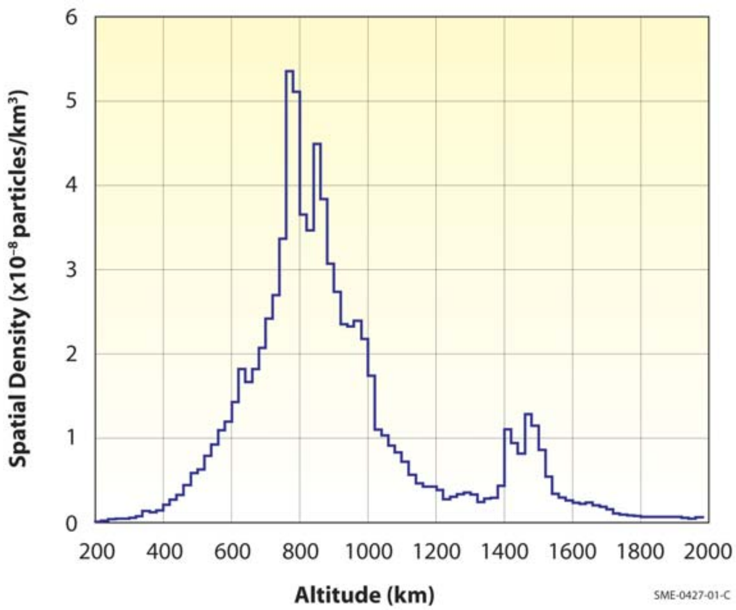

Figure 2: Orbital Debris Population in LEO as of January, 2011.

The implication of the interaction of the debris population with the atmosphere is that irrespective of the level of future space activity, the debris density below about 500 km will not change greatly. Whatever debris is created will rapidly be removed by the atmosphere.

DECAY PROFILE FOR LOW LEO SPACECRAFT

Spacecraft at low altitudes experience relatively high levels of aerodynamic drag (and also aerodynamic torque). As shown in Fig. 3, if no orbit maintenance burns were done, a typical spacecraft would decay and re-enter the atmosphere from an initial 300 km circular orbit in about 23 days at solar maximum and 70 days at solar minimum. As shown in Fig. 4, a similar satellite in a 200 × 500 km elliptical orbit will re-enter in about 21 days at solar maximum and in about 45 days at solar minimum.

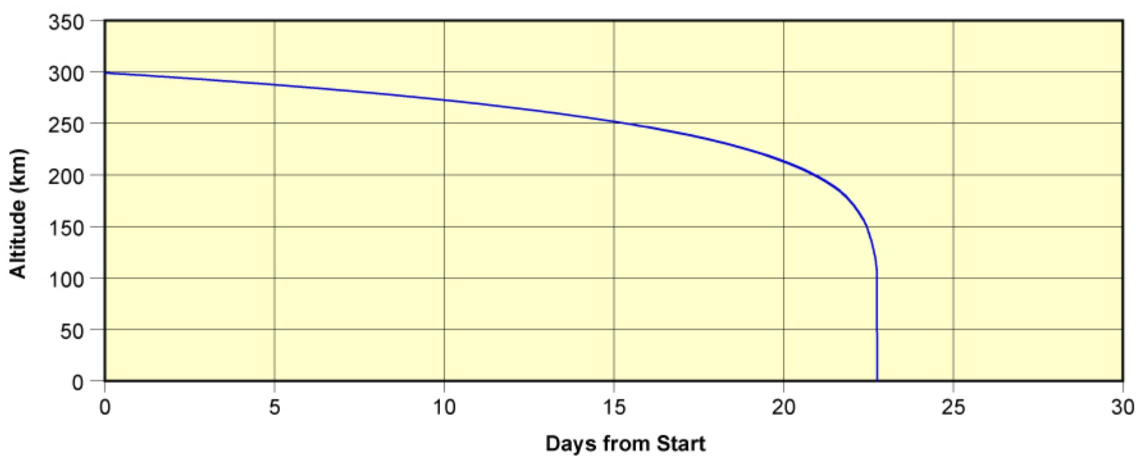

Figure 3: Typical spacecraft orbit decay at solar max with no orbit maintenance from an initial 300 km circular orbit. Satellites without orbit maintenance will re-enter the atmosphere very quickly. In this case, the satellite would re-enter in about 70 days at solar minimum.
(Figs. 3 and 4 were produced from the web-based version of Fig. 9-15 of Wertz.[25] Readers are encouraged to try similar plots on other orbits of possible interest.)

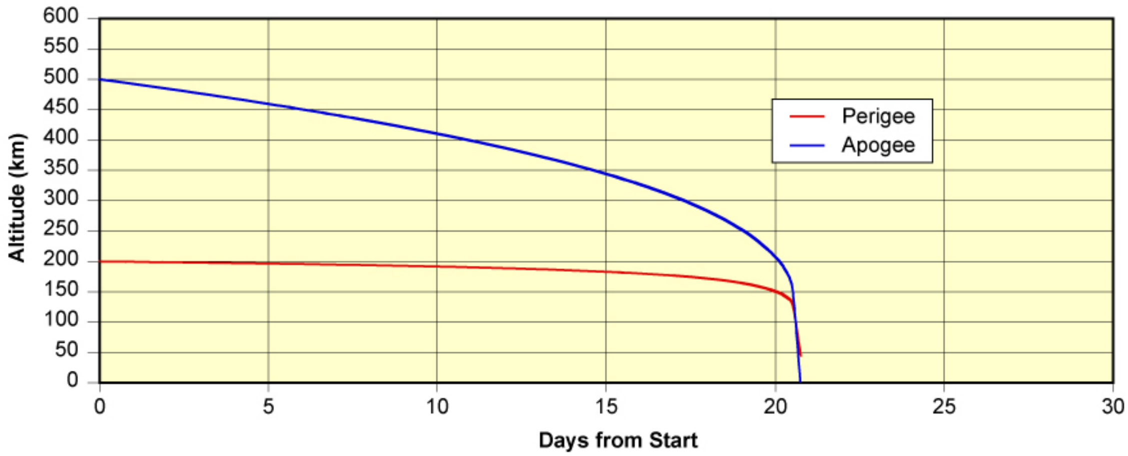

Figure 4: Typical spacecraft orbit decay at solar max with no orbit maintenance from an initial 200 km × 500 km elliptical orbit. In this case, re-entry would occur in about 45 days at solar minimum.

Figures 3 and 4 show the principal differences between orbital decay from circular and elliptical orbits. In the circular orbit case, decay begins immediately when orbit maintenance stops. As the orbit decay progresses, the satellite gets deeper and deeper into the atmosphere and the decay rate accelerates. If we recover the satellite at some later time, but before re-entry, we may or may not be able to recover the orbit because we will have gone deeper into the atmosphere where the decay rate has increased. If we are able to recover the orbit, we will have used excess delta V because we will have spent time in denser regions of the atmosphere.

Several things are different in the elliptical orbit case. Because the atmospheric density is decreasing exponentially as we go up in altitude, essentially all of the orbit decay will occur at perigee, which means that perigee will not change and apogee will decrease. This creates basically a two-step process for elliptical orbit decay as can be seen in Fig. 4. In the first step, perigee remains nearly constant while apogee decays. When the orbit becomes circular, the spacecraft quickly spirals down and re-enters. Notice also that because perigee remains nearly constant, the rate of decay of apogee is nearly constant over most of the range, then increases sharply prior to re-entry. What this means in practical terms is that there is relatively little harm in orbit maintenance outages, so long as recovery occurs before re-entry. Perigee remains nearly fixed, so all that has to happen after recovery is to raise apogee to its previous value. Because the decay rate has changed very little, there is no added penalty due to excessive decay. We simply have to replace the delta V that wasn't applied during the period that orbit maintenance wasn't working. **In this respect the MEVLO is a fail-safe orbit. In the event of an orbit maintenance failure, nothing bad happens for a period of time until relatively near the time that the satellite re-enters.** Recoverable failures do indeed occur in space systems and, for example, happened on UoSat-12 during the testing of autonomous orbit maintenance.[23]

OTHER ADVANTAGES OF MEVLOS

There are other significant advantages to MEVLOs. As can be seen from Figs. 3 and 4 above, the 300 km circular orbit has about the same lifetime due to orbit decay as the 200 km × 500 elliptical orbit. However, the elliptical orbit has a much lower perigee and, therefore, much resolution on the Earth when at perigee. As shown in Fig. 5, a given resolution at nadir can be achieved with a smaller, and therefore lighter and much lower cost, telescope at low altitude. A 0.5 m aperture telescope at 200 km has the same ground resolution at nadir as a 2 m aperture telescope at a more traditional altitude of 800 km, but at a cost of millions, rather than billions, as discussed in Sec. 6.

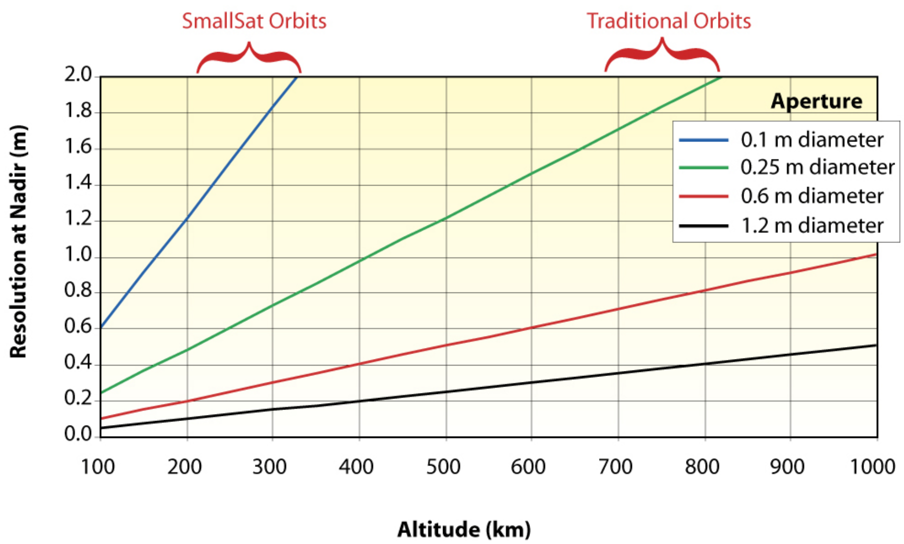

Figure 5: Resolution vs. Altitude for Low-Altitude orbits and Higher Altitudes used for more Traditional Systems.[26]

This advantage is substantially increased with active Earth observation payloads, such as SAR or lidar. For active payloads the power required goes as the 4th power of the distance. This relationship means that an active payload at 200 km would require 256 times less power than a similar payload at 800 km. This, of course, can have a dramatic impact on the size and cost of the payload and the spacecraft that must support it.

A second advantage of the very low orbits is the benign radiation environment. The denser atmosphere at low altitudes removes radiation from the environment, as well as orbital debris. At altitudes below approximately 1,000 km, the radiation dose increases as approximately the 5th power of the altitude.[18] Therefore, spacecraft in MEVLOs typically do not have significant radiation problems with the natural environment.

A significant difference between traditional low Earth orbits and MEVLOs is that spacecraft in very low orbits are often, though not necessarily, designed to have shorter design lives and be much lower cost. For military missions this distinction is typically between *strategic missions* with a long lifetime, high cost, and global focus vs. *tactical missions* with a shorter lifetime, dramatically lower cost, and focus on a particular geographic area or latitude band. Key characteristics of these two types of missions are given in Table 1.

Table 1: Characteristics of Strategic Assets (long lifetime, very high cost) vs. Tactical Assets (shorter lifetime, very low cost).

Strategic Asset (e.g., ISS, Hubble)	Tactical Asset (e.g., Car, Helicopter, SmallSat Constellation)
National Asset with one "Owner"	Locally owned and controlled asset with many owners and users
Irreplaceable in a contested environment	Immediately replaceable at modest cost
Loss is a major, long-term setback	Loss results in only a modest increase in cost
Has to cover all the world all the time, with all possible sensors	Can concentrate resources when and where they are needed (more economical and more responsive)
System does not respond well to changing world events or new technology (may be able to change coverage or operations approach)	Responsive to world events and to development of new technology
A single Concept of Operations (CONOPS) driven by national priorities	Multiple CONOPS solutions driven by the needs of the individual owner and user
Needs 100% reliable large launch (hard to achieve)	Benefits greatly from low-cost responsive launch
Built to projected need (as much as 25 years in advance)	Built to inventory; customized as needed; launched on demand
Zero defects mandate—extremely costly	Best industrial practices; great cost reduction

The properties in Table 1 are expressed in terms of military missions, but often apply equally to scientific, commercial, or civil missions in low Earth orbit or beyond. Thus, if JWST fails on launch or is hit by a large piece of debris at any point, it will be a major setback for science. In a distributed constellation of small scientific satellites, the loss of a single satellite for whatever reason is simply a modest loss of performance or increase in cost. Of course, there are some missions, such as the exploration of distant galaxies that may be much better done by a single very large, monolithic spacecraft and some, such as the exploration of multiple asteroids, that may be better done by a collection of smaller, much lower cost, spacecraft.

MEVLO ORBIT SELECTION

Traditionally, most spacecraft fly at altitudes above 500 km in order to maximize lifetime and minimize the propellant required for drag make-up. Typically, this has meant flying in the range of 700 to 900 km, an altitude range that maximizes the potential problem with orbital debris. In addition, if the satellite fails at any point or runs out of propellant (or doesn't have a de-orbit propulsion system), it contributes to the orbital debris problem. As in the case of Iridium 33 and Cosmos 2251, a satellite that runs into debris can create thousands of new debris particles, many of which will be too small to track (i.e., smaller than about 10 cm in diameter with present tracking technology).[17]

Many spacecraft have flown successfully at very low altitudes. The ESA GOCE gravity gradiometer mission is currently flying in this regime at 250 km and taking precision measurements. It is using very-low-thrust electric propulsion to continuously overcome drag so as to create a "drag-free" orbit. The CORONA surveillance spacecraft also flew in this regime with altitudes ranging from 165 to 460 km. (The KH-4B flew at 150 km and the KH-6 flew at 172 km.) Photos taken at the very low altitudes were typically blurred due to atmospheric torque and the resulting jitter, but the exposures were relatively long and the spacecraft itself was not designed to be aerodynamic.[3]

The principal disadvantage of flying at very low altitude is the delta V, and therefore propellant mass, required for drag make-up. The delta V per orbit required for drag make up is equal to the change in velocity per orbit due to drag. For the simple case of a circular orbit, this is given by:

$$\Delta V_{rev} = \pi (C_D A/m) \rho a V \tag{1}$$

where ΔV_{rev} is the required delta V per orbit, C_D is the dimensionless drag coefficient, A is the spacecraft cross sectional area perpendicular to the direction of the velocity vector, m is the spacecraft mass, ρ is the atmospheric density, a is the semimajor axis, V is the orbital velocity, and the term $m/C_D A$ is the *ballistic coefficient*.[25] (See the reference for equations for elliptical orbits and a more detailed discussion of the computation of the drag coefficient.) Typical values of the ballistic coefficient range from 20 kg/m^2 for a spacecraft with large deployed solar arrays to 200 kg/m^2 for compact, dense spacecraft. See Wertz, Table 9-10 for values of the ballistic coefficient for representative spacecraft.[25]

Typical values of the total delta V per year required for drag make-up for a spacecraft with a ballistic coefficient of 100 kg/m^2 are shown in Fig. 6 for circular orbits and in Fig. 7 for MEVLOs. (Note that in Fig. 7, the horizontal coordinate is the perigee altitude. The semimajor axis or mean altitude will be just the average of the perigee and apogee altitudes.) For convenience, typical numerical values of the required delta V for both circular and elliptical orbits are given in Table 2 and the corresponding orbit lifetimes without orbit maintenance are given in Table 3. As can be seen from Eq. (1), the required delta V is just inversely proportional to the ballistic coefficient so that values can be easily calculated for any desired spacecraft configuration.

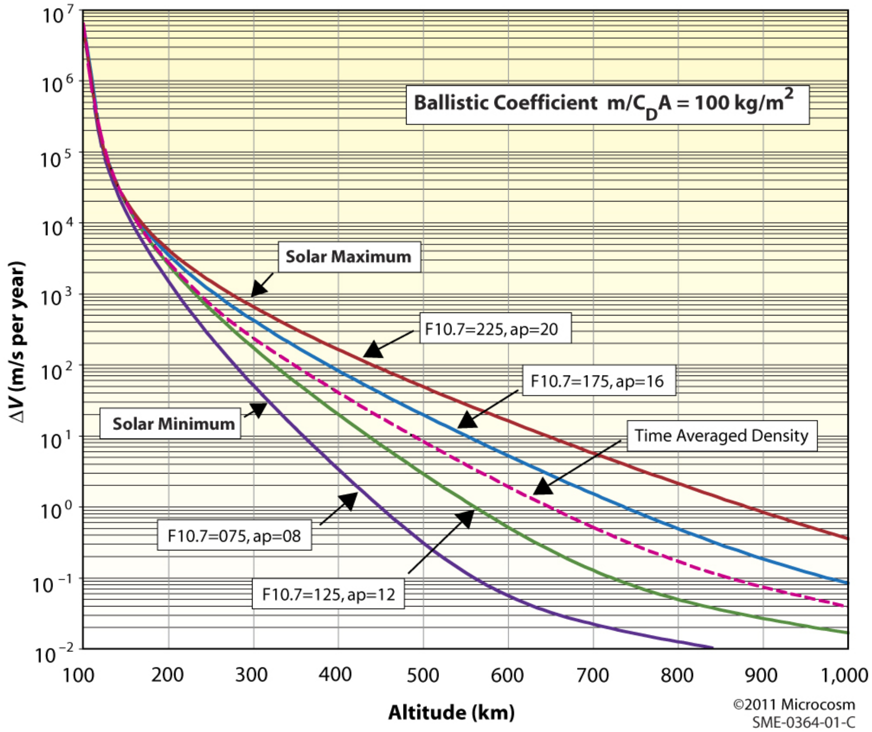

Figure 6: Altitude Maintenance Delta V for Circular Orbits at Various Altitudes and a Ballistic Coefficient of 100 kg/m^2.[27]

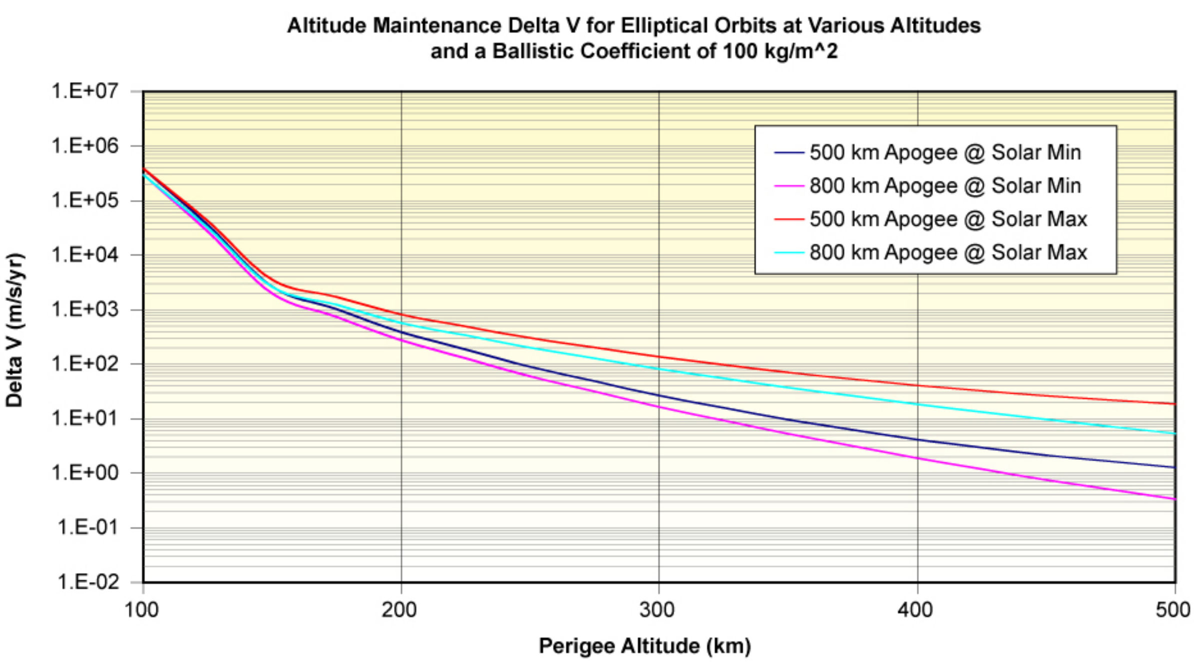

Figure 7: Altitude Maintenance Delta V for Elliptical Orbits at Various Altitudes and a Ballistic Coefficient of 100 kg/m^2.

Table 2: Delta V per Year Required for Orbit Maintenance. Assumed Ballistic Coefficient of 100 kg/m^2.

Orbit	Solar Min	Solar Max
200 km Circ	2,110 m/s/yr	3,720 m/s/yr
300 km Circ	103 m/s/yr	420 m/s/yr
350 km Circ	30 m/s/yr	176 m/s/yr
400 km Circ	10 m/s/yr	79 m/s/yr
500 km Circ	1 m/s/yr	19 m/s/yr
200 km × 400 km	480 m/s/yr	1,030 m/s/yr
200 km × 500 km	388 m/s/yr	825 m/s/yr
200 km × 800 km	275 m/s/yr	580 m/s/yr
300 km × 500 km	27 m/s/yr	137 m/s/yr
300 km × 800 km	17 m/s/yr	82 m/s/yr

Table 3: Lifetimes due to Orbit Decay. Assumed Ballistic Coefficient of 100 kg/m^2.

Orbit	Solar Min	Solar Max
200 km Circ	2.3 days	1.6 days
300 km Circ	76 days	25 days
350 km Circ	289 days	67 days
400 km Circ	967 days	162 days
500 km Circ	8,250 days	777 days
200 km × 400 km	26 days	13 days
200 km × 500 km	46 days	22 days
200 km × 800 km	123 days	58 days
300 km × 500 km	524 days	116 days
300 km × 800 km	1,800 days	373 days

In addition to the delta V required for orbit maintenance, the other disadvantage of flying low is the reduced coverage from low altitude. At low altitudes, the coverage swath width for a given minimum working elevation angle is proportional to the resolution, and the coverage area at any one time is proportional to the square of the swath width. Simple formulas that take the curvature of the Earth into account are given by Wertz and are tabulated on the inside rear cover of that reference.[28]

Orbit selection for MEVLOs then comes down to balancing good resolution, reduced instrument (and, therefore, spacecraft) size and cost, and reduced orbital debris issues (both in terms of collision probability and contribution to the long term debris problem) against the delta V required and reduced coverage. Higher altitude satellites will generally have a longer design life and, therefore, potentially lower cost per year, but in more modern spacecraft this may be more than offset by the increased debris risk and the historically dramatically high cost of trying to design spacecraft for very long life. In addition, the typically shorter design life of MEVLO spacecraft allows them to take advantage of new technology, particularly in the dramatic performance growth of small electronics and the use of composite technologies.

NANOEYE — A SPACECRAFT DESIGNED FOR MEVLO OPERATION

NanoEye, shown in Fig. 8, is a small spacecraft being developed by Microcosm for the Army and designed specifically for MEVLO operation.[19, 20] Because the mean free path of the atmospheric molecules is much longer than the spacecraft, NanoEye is not aerodynamic in the traditional sense of the word. Atmospheric interaction is a series of individual interactions between the spacecraft and the molecules. As shown in Fig. 8, the spacecraft is designed to minimize both drag and torque. The spacecraft rolls about its longitudinal axis and the mirror on the side rotates about an axis perpendicular to roll such that the payload can see anywhere in the full spacecraft sky (including the Earth) while still keeping the wedge facing in the direction of motion as shown in Fig. 8B. The top of the wedge contains CubeSat solar array panels. The bottom of the wedge is simply an "aerodynamic panel" to reduce drag and balance the torque. Monatomic oxygen (O) will stick to either panel and cause both drag and torque. Much of the diatomic nitrogen (N_2), however, will bounce at a shallow angle, reducing the nitrogen drag on the spacecraft by about 80%.

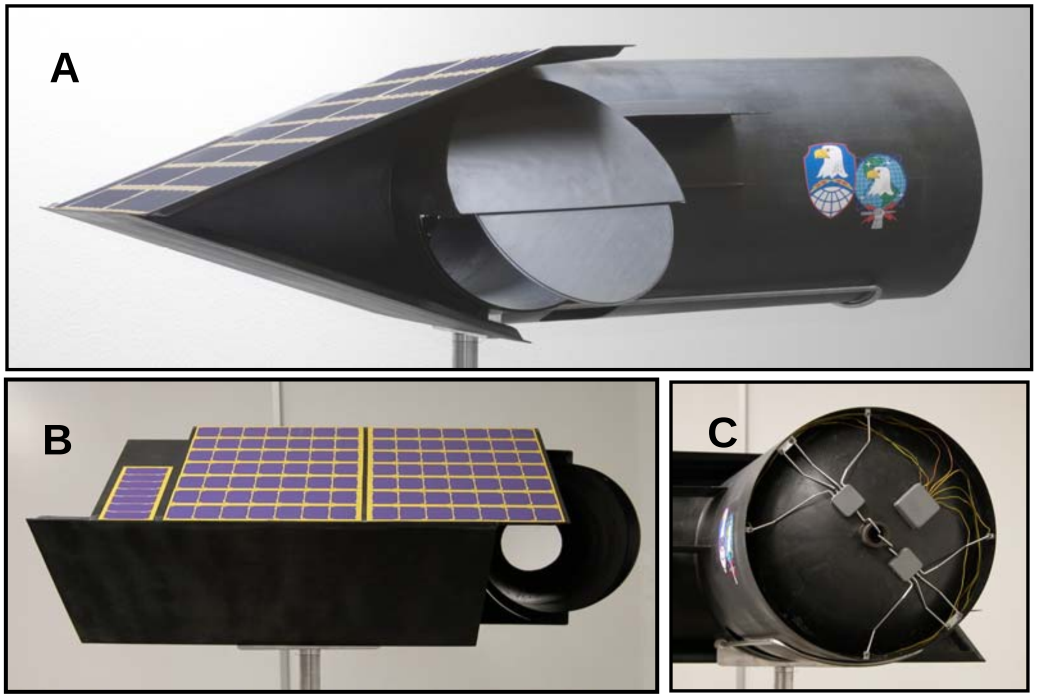

Figure 8: Full-Scale NanoEye Spacecraft Model. The wedge or V-shaped pair of panels is always forward facing. The 8 thrusters shown in (C) provide orbit control and the coarse outer control for roll, pitch, & yaw.

The NanoEye structure and propulsion system are also designed to overcome drag. Except for the rotating scan mirror assembly, the entire structure and propellant tank is a single, unibody composite structure. The portion of the main tube behind the mirror (i.e., the right half of the spacecraft in Fig. 8A) is a propellant tank holding somewhat more than 50 kg of hydrazine. This allows ample delta V for controlling drag. On the rear of the tank, shown in Fig. 8C, there are 8 small Aerojet thrusters, developed and flown on the LEAP program. Each thruster weighs 5.4 g and provides 1 lbf of thrust at 1000 psi. The NanoEye tank nominally operates at 550 psi, such that the thrust will be about 0.55 lbf = 2.5 N per thruster.

In Fig. 8C, the thrusters on the top and bottom provide pitch control, the two on the left and right provide yaw control, and the 4 at approximately 45 deg provide roll control and are canted 45 deg from straight back. The 4 pitch and yaw thrusters provide orbit control and drag make-up. Off-modulation during orbit control is used to account for either thruster misalignment or offset of the center of mass (CM) with respect to the net thrust vector.

The 4 orbit control thrusters provide a total of 10 N of thrust in the forward direction, which is somewhat more than 500 times greater than the largest anticipated drag force at solar max. However, there is considerably more margin than that if an elliptical orbit is used, instead of a circular one. First, the maximum anticipated drag force is at perigee and is 0.02 N, but the maximum drag force at apogee in the same orbit is only 0.000 04 N, such that there is far more margin than just the factor of 500 at perigee. However, there is a second factor due to the way that elliptical orbits decay. As discussed above, if the thrusters stop working at any point perigee remains essentially unchanged and apogee begins to drop at a constant rate of about 15 km/day for NanoEye at solar max. If the thrusters are restored within a few days, the original orbit can be recovered with essentially no loss in overall delta V. For low-altitude orbits, an elliptical orbit is much safer than a circular orbit.

One remaining issue is the operational problem of doing orbit control burns on nearly every orbit in order to maintain the orbit parameters. Recall from Fig. 4 that perigee effectively does not change due to short-term decay. It is apogee that decays first. While it may not be necessary to do burns on every orbit, they will certainly be done more frequently than once a month, which is the typical interval for LEO spacecraft and which often represents full-time operations work for 2 people. Fortunately, orbit maneuvers can be done entirely autonomously on board the spacecraft by using

Microcosm's autonomous orbit control software that has flown successfully on both UoSAT-12 and TacSat-2.[14, 23, 24] The software not only maintains the orbit, it minimizes the propellant needed to do so and, more importantly, maintains very precise timing of the orbit parameters, which is important for two reasons. Most important, if we have a constellation of multiple NanoEyes we need the spacecraft orbits to be synchronized with respect to each other. This synchronization process would be a demanding, and possibly error-prone, task if it had to be done by someone sitting outside the commander's office in the field, but will be done automatically on-board for NanoEye. Second, autonomous orbit control provides the potential for precision planning if we chose to do so. If, for example, we want a particular spacecraft to fly over the Eiffel Tower and take a photograph looking north–northeast at noon next Friday, NanoEye will be there and do that to within 0.1 sec. This is a potentially important characteristic for both military planning and some civil applications.

In addition to drag at low altitudes, there is also the problem of atmospheric torque, which is directly proportional to both the atmospheric density and the offset between the center of mass (CM) and center of pressure (CP). If we assume a worst case (CP-CM) offset of 10 cm (slightly more than half the radius of the main body of the spacecraft), then the worst-case aerodynamic torque at perigee at solar max is 0.0010 N-m = 1 mN-m. This torque would apply only during perigee passage and would be about 700 times less at apogee in the same orbit. The 2.5 N pitch and yaw thrusters have a nominal offset from the center line of the spacecraft of about 18 cm, which provides a thruster torque of 450 mN-m, i.e., 450 times the worst case projected torque. If we choose to cant the thrusters away from the CM of the spacecraft by 18 deg, we would reduce the net forward force by about 5% and more than double the available thruster torque, i.e., increase the worst-case torque margin to about a factor of 1000.

Finally, a potential problem to be considered in spacecraft control is plume impingement in which the plume from the thruster impinges on some portion of the spacecraft and produces an unintended torque that has, on some occasions, caused spacecraft to tumble. Typically, this problem is most significant when the plume impinges on a portion of a deployed solar array or antenna because the lever arm can be very long. This situation does not apply to NanoEye because there are no deployables. However, all of the thrusters are located relatively close to the tank skirt and the Planetary Systems Corp. Lightband attachment to the launch vehicle and it is likely that there will be some plume impingement on these parts. Fortunately, plume impingement on the nearby elements will increase the torque in the intended direction, thus making the thruster somewhat more efficient at providing torque and further increasing the torque margin. It is typically very difficult to quantify the magnitude of the plume impingement and the resulting torque. In the case of NanoEye, we anticipate calibrating on orbit the total torque from each thruster to account for all of the major error sources—thrust vector misalignment, uncertainly in the position of the CM, and plume impingement. The only consequence of this on-orbit calibration, other than to more accurately compute attitude maneuvers, is to reduce slightly the propellant budget for attitude maneuvering. However, this is a very minor contribution to the overall propellant budget. The bottom line is that aerodynamic torque, while potentially much larger than for traditional high altitude spacecraft, is not a problem for NanoEye.

CONCLUSIONS

Orbital debris removal or mitigation is, at best, a challenging problem to resolve. An alternative, long-term solution is to find orbits that are safe, provide a good platform from which to make Earth observations, and do not allow the build-up of long-term debris. ***Moderately Elliptical Very Low Orbits*** (MEVLOs) are LEOs with perigees below approximately 300 km, apogees below approximately 500 km, and eccentricities in the range of 0.015 to 0.030. These orbits have the following principal characteristics:

- Moderate to long life with a reasonable propellant budget
- Fail safe, in that they can recover from a temporary loss of propulsion (due, for example, to a recoverable computer or software failure) with essentially no loss of system lifetime
- Substantially reduced system cost by allowing much higher resolution Earth observations with a smaller aperture, much more economical instrument
- Much lower debris collision probability, because the debris density below approximately 500 km is (and will continue to be) much less than at traditional satellite altitudes
- Can not contribute to the long-term debris problem because any debris that is created will decay and re-enter within a few weeks to a few years

Microcosm has created a spacecraft design and a concept of operations to take full advantage of this new orbit regime and address the principal problem areas of increased drag and the need for frequent orbit maneuvers. Historically, the principal disadvantage of orbits below about 500 km is that spacecraft at this altitude would decay and re-enter in a time period commensurate with the spacecraft operational lifetime. Given the fundamental problems associated with orbital debris, this "disadvantage" is, in fact, the fundamental characteristic that makes these orbits an excellent choice for future space missions.

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