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Extrapolations of the commercial orbital traffic within 25 years imply an increase of as much as two orders of magnitude in the mass placed in LEO annually; attention is accordingly given to the upper limits placed on such activity by debris hazards, and especially to the 'cascade' effect that would ultimately render LEO unusable. An orbiting spaceport in LEO is recommended as a long term solution to this problem. The spaceport would have reusable orbital transfer stages capable of accessing desirable orbits in cislunar space while minimizing orbital traffic in LEO. O.C.

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# LIMITS TO GROWTH IN LOW EARTH ORBIT

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## Abstract

Space powers currently operate not only domestic programs but also advertise launch services internationally to commercial entities as well as non-spacefaring nations. Published extrapolations of the commercial Earth-to-orbit traffic within 25 years imply an increase of as much as two orders of magnitude in the mass placed in low Earth orbit annually and a rather larger increase in passenger traffic. Upper limits to levels of space activity are set not only by launch capacity and launch cost but also by the debris hazard in the limited confines of near-Earth space. The insidious characteristic of the debris hazard is the possibility of a "cascade" effect, rendering LEO unusable in a worst case scenario. In particular, uncontrolled objects gradually decay through lower altitudes, making the lower limits of LEO, which are most easily accessible with less advanced and less expensive launch systems, the most vulnerable to eventual disruption. Agreements to restrict the number or type of launches are unlikely in the face of demands from developed and developing nations for access to the benefits of the space environment. The most universally acceptable, long term solution for alleviating environmental pressure on LEO may be an in-space transportation infrastructure, permitting international access to locations outside of LEO. A key element would be an orbiting spaceport in LEO with reusable orbital transfer stages capable of accessing desirable orbits in cislunar space while minimizing undesirable impacts on the delicate near-Earth orbital environment.

## Usage of Low Earth Orbit

In October, 1957, the Soviet Union placed into orbit the world's first artificial satellite. Soon, the United States followed suit. Early satellites had objectives that were scientific or military (usually reconnaissance) in nature. Since the first generation of launch vehicles were limited in payload capacity, the first man-made objects were placed in the lowest energy orbits consistent with mission objectives. A minimum condition for long lived satellites is the achievement of a perigee altitude above the sensible atmosphere to minimize drag, which leads to orbital decay and atmospheric reentry.

As launch vehicle capability improved, satellites could be placed into higher energy orbits. In particular, geostationary orbit (GEO) became a desirable location for communication satellites and Earth observation platforms. Eventually, the number of satellites proposed for GEO above the Earth's equator became so large that a danger of signal interference arose. These potential conflicts in the usage of a limited range of orbital parameters and frequency allocations was resolved by a series of international agreements.

As Earth-to-orbit launch capability has grown in payload capacity, it has also proliferated throughout the nations of the world. Currently, the European Space Agency, the Japanese space agencies ISAS and NASDA, and the People's Republic of China have built launch complexes and routinely launch satellites. In addition, the space-faring nations have formed marketing organizations to sell launch services to countries without their own capability and to corporations desiring to launch satellites.

Proliferation of launch capacity has been accompanied by an increase in the variety of uses for LEO. Research satellites and military satellites are now accompanied by commercial satellites. Since low Earth orbits are used as parking orbits prior to transfer to high Earth orbits, spent upper stages pass through LEO on eccentric transfer orbits.

The size and the complexity of satellites in LEO are also growing. The Hubble Space Telescope is awaiting launch by the Space Shuttle. It is the first in a series of Great Observatories planned by the U.S. space science program. The Great Observatories will be placed in LEO so that they may be serviced by sorties from the U.S. manned low Earth orbit space station. The sorties themselves will represent an escalation in the complexity of activities in LEO.

The launching of humans into orbit places temporary orbiting objects into LEO which are considerably larger than the usual scientific, military, or commercial spacecraft. At the present time, the Space Shuttle is the largest spacecraft in LEO, but its missions never last longer than about a week. However, permanent human presence in space requires quite large structures in permanent orbits. Skylab was the first such station and was followed by the longer-lived Soviet stations, Salyut and Mir. When the U.S. space station is established, it will be the largest structure in space and will be the focus of many operations. Although long term Soviet space station plans have not been made public, most observers acknowledge that the Mir complex has the potential to equal or exceed the scale of the U.S. station in comparable time frames.

Thus, the first thirty years of the Space Age have seen a more or less steady growth in the usage of low Earth orbit space. That growth has expressed itself in a number of variables - number of users, number of satellites, size of satellites, and complexity of operations. The population explosion in LEO reflects the evolving maturity of launch technology. Since a great deal of effort is in progress to lower launch costs and to simplify launch operations, a continued growth of orbiting mass into LEO is assured.

## Future Growth of Activities in LEO

Predictions of the rate of growth of space development are notoriously unreliable. The scope of the Apollo program was totally unanticipated in 1960. On the other hand, attempts to estimate the investment potential of space commercialization typically have proved overoptimistic (1),(2)).

Nevertheless, the last 30 years has seen a qualitative as well as quantitative growth in launches to low Earth orbit. The launch capability could be described as monotonically increasing except for the termination of the Saturn rocket program in the U..S. which eliminated the world's only operational heavy lift vehicle. The appearance of the Soviet Energiya, the ESA Ariane 5, the Japanese HII, the Chinese Long March 3, and a program for a new U.S. heavy lift vehicle suggest that the total mass placed in LEO will continue to grow.

Specific large programs which will utilize this enhanced launch capacity include the planned U.S. space station and the much-debated Strategic Defense Initiative. Although both the Europeans and the Japanese are partners in the U.S. space station, they also speak about independent mannable or manned LEO facilities. The planned scale of the Soviet manned station has not been stated, but the new Mir configuration clearly is designed for expansion. In the U.S. private sector, excluding communications satellites, the Industrial Space Facility from Space Industries, Inc., represents a class of permanent platforms that are mannable, though not permanently manned.

In every country plans are being formulated for ambitious orbital operations, some of which are quite extensive. In the U.S., the manned space station not only requires a steady schedule of logistics support from the ground but also will interact with co-orbiting free flyers and will service Earth resources platforms in polar orbit and large, complex scientific satellites such as the Great Observatories.

In the Soviet Union, the Mir station probably will evolve into similar functions. "While Mir will eventually be permanently manned...the completed Mir complex (including specialized modules for astrophysics, Earth resources, materials processing, and biological studies) appears to be merely a transition phase to a very large permanent space station complex..."(3).

In all likelihood, the scale of space development will grow dramatically when the economic resources of the private sector in the Western economies are brought to bear. To cite an example, Yamanaka and Nagatomo (4) have evaluated the market for space communications, space remote sensing, and space materials processing within the Pacific Rim economies in the first decade of the 21st Century. These authors foresee a space infrastructure consisting of co-orbiting manned and unmanned facilities associated with the U.S. space station (an "Orbital Space City"), remote sensing satellites in high inclination LEO orbits, and a GEO service station for GEO platforms. Their estimate of the steady state human population in orbit is approximately 1000 in the years 2005-2010. The traffic to and from the Orbital City is estimated to be 120 persons and 120 tons of cargo per day. This visionary estimate for the Pacific Rim economic development of space is equivalent to a fifty-fold increase in the mass of payloads sent to LEO and an even larger increase in passenger traffic over what is launched today throughout the world.

The methodology used by Yamanaka and Nagatomo could be applied as well to the "North Atlantic Rim" economies. Although the projected GNP for the Atlantic countries is smaller than that of the Pacific nations, the estimates of the scale of space activities ought to be comparable. The seeds for this growth in space activity reside in the formation of broadly based international consortia such as INTOSPACE.

Thus, some futurists foresee a growth in Earth-to-orbit launch activity of one to two orders of magnitude over a generation. The reality of this rate of growth might be challenged on the basis of the validity of the assumption of the level of investment by the private sector. In any case, the trend is correct; and the scale is plausible though uncertain.

There exists, however, a major question which needs to be addressed: Are there any physical limits to economic development of low Earth orbit in addition to financial and political considerations?

## Low Earth Orbit: A Fragile Environment

In the popular view, "Space" is both empty and infinite. Low Earth Orbit (LEO) is neither.

Low Earth orbit is a spherical shell bounded below by the Earth's atmosphere and above by the Van Allen belts. Satellites cannot orbit below 200 km due to atmospheric drag. Satellites higher than about 1000 km must be designed to withstand the radiation doses from trapped charged particles in the Earth's magnetic field. This latter boundary condition is particularly important for manned operations. Even for the planned U.S. station at approximately 500 km the cumulative radiation dose is perceived as limiting to crew duty cycles and to total career time in space.

A *de facto* bound on the upper altitude of the LEO shell is created by the inverse relation between deliverable payload mass and attainable orbital altitude for current launch vehicles. The payload capacity of the Space Shuttle was a major factor in the selection of the U.S. space station orbit. Associated free flyers and serviceable platforms will be in circular orbits at altitudes not vastly different from the main station. The Soviet Mir and Salyut complexes orbit at approximately 400 km, probably due to launch vehicle considerations.

The U.S. Space Command currently has the responsibility, formerly charged to NORAD, to track and catalog all manmade objects in space. However, within this volume of space called LEO, the sensitivity of the radar system used limits detection to objects 10 cm in size. At the beginning of 1987, the catalog contained over 6000 objects, only 5% of which were operational payloads. Approximately half of the objects are debris fragments from explosions or unexplained breakups (5) Some of the mysterious breakups are strongly suspected to have resulted from collisions.(6)

The flux of objects in the size range tracked by radars exceeds the natural meteoroid flux by several orders of magnitude. The flux of undetected smaller objects is unknown but is thought to approach the meteoroid flux in the millimeter size range. As a comparison, the mass of natural meteoroids at altitudes less than 2000 km at any one time is less than 250 kilograms. The mass of the known orbital debris population is approximately 2,000,000 kilograms.

The number of objects is higher than it has ever been and has been growing since records began to be kept in 1970. Although atmospheric drag does remove debris from orbit, source mechanisms have produced objects faster than they are lost with the exception of a brief period from 1978 to 1980. At that time a temporary reduction in the satellite breakup rate fortuitously combined with excess solar activity, which caused the atmosphere to expand, thereby increasing the decay rate.

A large number of trackable objects are generated by fragmentation of satellites or spent upper stages during transfer of payloads to GEO. At first the fragments lie in approximately the same orbit, and the pieces have low relative velocities to one another. The pieces gradually separate, and their orbital planes precess at different rates. Over a period of a few months the longitudes of the ascending node are randomly distributed, and their average encounter velocity is approximately 10 km/sec. Thus, millimeter-sized particles can do considerable damage upon collision,even to spacecraft which started in the same breakup orbit.

The worst case occurs when the debris population grows to the point that collisions trigger a cascade of fragmentations, leading to runaway growth and rendering low Earth orbit useless. Su (7) has reported model calculations showing that the runaway condition occurs under almost any assumed rate of growth. High growth rates of launching activity trigger the catastrophe sooner than low rates.

Su first established a "baseline traffic model" by assuming that the number of trackable (by NORAD) objects placed into orbit for each year in the future will be the same as was placed into orbit in calendar year 1982. In other words, the baseline model assumes (optimistically) no proliferation of fragments due to satellite explosions such as those routinely occuring in LEO. It also includes losses of material from orbit due to atmospheric drag and even the enhancements of that loss mechanism due to increased upper atmospheric density during active portions of the solar cycle. The baseline traffic model shows steady but approximately linear growth in the detectable debris population. Its use as a lower limit is supported by the observation that the model underestimates the present debris population by about 15%.

Su then modifies the baseline by adding various rates of growth, ranging from 2% per year to 50% per year. Through a probabilistic model, he also allows enhancement of the debris population by means of collisional fragmentation. The linear growth in debris flux seen in the baseline model changes to an exponential growth.

Su arbitrarily defines a "critical" level in the flux when a space structure with a cross-section of 10 $m^2$ receives an average of 1 impact per year from particles larger than 4 mm. If we assume a growth rate in the traffic model of 2% per year, the critical flux level is reached at an altitude of 500 km in the year 2128. At that time the model predicts that over 96,000 detectable objects will be passing through the LEO volume.

If the methodology of Yamanaka and Nagatomo is applied to the North Atlantic nations as well as the Pacific Rim nations, the predicted level of space activity would correspond roughly to a growth rate of 20% per year. For this case the critical flux density is achieved at an altitude of 500 km in the year 2016, and the number of detectable objects in orbit is more than 260,000. Similarly, at 1000 km, the critical flux occurs two years earlier, when only 180,000 detectable objects are in orbit.

The traffic model implicitly assumes that the escalating number of launches in future years will always be carried out the same way they were in 1982. As Henley[8] points out, a U.S. space station reusable with Orbital Transfer Vehicles will perform transfers to GEO and other high orbits leaving less debris behind. Spent upper stages and various fixtures in transfer orbits will be a thing of the past. Thus, applying Su's model to Yamanaka and Nagatomo's Orbital City is not entirely appropriate.

On the other hand, the conduct of complex operations on orbit such as refueling, payload transfer, refurbishment, and maintenance is bound to generate debris through mistakes such as dropped tools or broken valves. Without experience in these on-orbit operations, the prediction of their contribution to debris is uncertain.

A second model calculation in Su's paper give some insight into the growth of the debris population in the space station era. To the baseline (no growth) traffic model, he adds the launch of 10 large structures, each 100 m in diameter, in the year 1995. In one case the structures are placed at an altitude of 500 km and at 1000 km in another case. We are most interested here in the calculation which assumes that the structures are controllable to the extent that they do not collide with each other.

No matter where the structures are put, the debris flux jumps about two orders of magnitude at all altitudes in the first 5 years. When the structures are placed at 500 km, the critical flux density and the runaway condition does not occur for approximately 100 years. However, when the structures are placed at 1000 km, Su reports that the critical flux density is reached in 10 years at all altitudes. The reason for the difference, according to Su, is the lower atmospheric drag, and thus longer orbital lifetimes, for debris particles created at the higher altitudes.

The details of the results of the debris calculations are sensitive to internal assumptions in the model such as the distribution of momentum and energy among ejecta from hypervelocity impacts in space. Su[9], in an unpublished internal memorandum, discusses limited laboratory evidence that suggests a partitioning of energy and momentum according to the mass of ejected particles. Particles with small mass may be ejected with velocities exceeding terrestrial escape velocity, implying that the population of smaller particles may not be as large as predicted in the earlier calculations. Subsequent runs of the debris model using the modified hypervelocity impact ejecta characterization do show a reduced debris population density in the millimeter-sized particles but do not yield qualitatively different conclusions relative to the runaway debris flux. Nevertheless, hypervelocity impacts need a great deal more study.

In summary, a model of debris generation in LEO shows that steady growth of Earth-to-orbit launch rates will result in an eventual runaway impact flux. An evolution of space transportation systems to manned orbiting spaceports and reusable orbit transfer vehicles can modify the rate of growth of the debris population but does not solve the fundamental problem. In fact, the presence of human crews in space turns the ever-increasing probability of a large impact into a life-threatening situation long before a debris population runaway occurs. We must conclude that future visions of large-scale operations in space cannot come to fruition until dramatic changes are made in the nature of space operations.

## Searching for a Solution

The debris problem could be solved directly by the invention of a device or class of devices that remove debris from orbit. In one proposal a large area, low density satellite slows down debris by impact - without creating any more debris. Other ideas include vaporization of particles using lasers or eroding particles using streams of dust. None of these concepts have yet been demonstrated.

If no "Orbital Sweeper" can be invented, then we must change the path along which space utilization is proceeding. For example, international policies might be established to minimize the number of extraneous pieces left in orbit after a successful launch and to reduce the probability of explosions on orbit. The launching nations already are working to this end, but the policies are not entirely successful. For example, the recent launch of the Ariane left about a dozen objects in GEO transfer orbit - more than expected. The destruction of the Solwind satellite left several hundred detectable (and perhaps thousands of marble-sized) objects in orbit. In the past five years approximately 10 Soviet satellites have fragmented, generating almost 200 cataloged pieces of debris.[10] At the present time, approximately 3% of all launches lead to explosions on orbit.

Some have suggested placing satellites in high altitude junkyard orbits when they have outlived their usefulness. Such a policy may not solve the problem because only about 5% of the objects in LEO are operational payloads.

When the environment deteriorates to the point that satellites are obviously being disabled by impacts, then regulation by international agreements or treaties will become inevitable. A regulatory environment will stifle private investment and will be disadvantageous to nations just developing launch capabilities or space research and utilization programs.

Development of completely reusable space transportation systems can, in principle, reduce the extraneous mass in orbit. In Su's[7] "large structure" calculation, the debris flux reached a runaway condition due to erosion of the structures by a background of growing debris generated by ongoing expendable operations (baseline model). If expendable operations are phased out in favor of the reusable system, the erosive flux in Su's model decreases.

However, the heart of such a system is a manned orbital spaceport, supporting complex operations. Orbiting spaceports can be built only by the wealthy, technologically advanced nations. Expendable vehicles will be the launch system of choice of the developing nations and of the private sector until services of a reusable system are freely available and affordable. The predictions of the future debris environment discussed here suggest that the entire low Earth orbit environment will remain at risk unless the international community can create a reliable, reusable transportation system capable of delivering payloads to high Earth orbits such as GEO.

On the other hand, a completely reusable system has its own vulnerabilities. Large transportation vehicles carrying cryogenic propellants could make orbital explosions much larger than ones we see today. Heavy human involvement in space will make the consequences of accidents much worse. In the long run, it may be wise to minimize the mass in LEO to lower the possibility that a single accident could trigger a catastrophic increase in the debris flux.

The reusable transportation system we have been considering will give us more choices of locations for space operations than we have now. An orbital transfer stage capable of carrying a payload from a 28.5 degree orbiting space station to a polar orbit or to GEO can also carry payloads to lunar orbit because the impulsive delta-V's for all these maneuvers are comparable. Thus we will have access to all of cislunar space.

In particular, payloads can be placed in halo orbits about the unstable Moon-Earth Lagrangian points. These orbits are actually three-dimensional lissajous figures which can be maintained with a small expenditure of propellant in the form of reaction control jets[11]. For example, International Sun Earth Explorer satellite was stationed at the Earth-Sun unstable point for four years before being transformed into the International Cometary Explorer in pursuit of the comet Giacobini-Zinner [12]. The halo orbits can be located anywhere in a large volume of space and have very low energy with respect of one another. Consequently, visits to multiple satellites can be made with very little expenditure of propellant. Debris generated in this volume leaves it immediately because, without propulsion capability, it falls immediately toward the Moon or toward the Earth. Obsolete payloads could be ejected from the Earth-Moon system using gravitational assists from either planet. Ultimately, a station at point L1 between the Earth and the Moon could be a staging point for manned missions to Mars.(11)

Finding a solution to the problem of catastrophic growth of debris flux in low Earth orbit is central to the whole future of space development. Choice of the final strategy may not be obvious and may not be a direct approach to near term fixes. If no simple technical solution is invented for debris removal, the difficulties of formulating and enforcing operational constraints on the spacefaring nations may force a more subtle approach. Quite possibly the threat of destruction of the fragile low Earth orbit environment will be the impetus to humankind to reach for the Moon and, by extension, the solar system.

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