Equatorial Low Earth Orbit (ELEO): An Orbital Incubator and Nursery

Siegfried Janson, Ph.D.
El Cajon, CA, 92019; 310.379.7060
siegfriedjanson@gmail.com

ABSTRACT

Recent research has shown that Equatorial Low Earth Orbit (ELEO) below 500 km has an exceptionally low space radiation environment that is ideal for long-term space settlements. The pressure vessel itself provides enough radiation shielding to enable decades of on-orbit habitation for an individual without exceeding radiation safety limits. My calculations using SPENVIS show that a minimum radiation "Incubator" region exists between 24^{o} inclination at 350 km altitude, which drops linearly with increasing altitude to 0^{o} inclination at 550 km altitude. Silicon-based spacecraft electronics inside a 1-mm thick aluminum hull would have a trapped particle dose rate ~4 orders-of-magnitude lower in the Incubator than in an ISS orbit. Single event upsets, however, will drop by only 2 orders-of-magnitude due to remaining galactic cosmic rays. With power supply modifications to mitigate the occasional latch-ups from galactic cosmic rays, plus replacement of short-lived components such as electrolytic capacitors, commercial off-the-shelf electronics should operate for decades. Even thin-film membrane spacecraft like BraneCraft, with only 10 microns of radiation shielding, could operate for many years without requiring radiation-hardened electronics. The ELEO Incubator is ideal for students and space startups wishing to flight test new space components, subsystems, and systems, potentially over decades of operation, without worrying about radiation degradation. It should be ideal for in-space computing centers; "the Cloud" above the clouds, and on-orbit manufacturing.

Use of reusable first stages in the Falcon 9 launch vehicles has already enabled a 6 X reduction in delivery cost to LEO: 1,900 USD/kg today vs. ~ 10,000 USD/kg ten years ago. By 2028, fully reusable SpaceX Starships should deliver 100,000 to 150,000 kg to LEO for ~30 million USD: about $200/kg. This price should facilitate an explosion of new manned and unmanned applications: orbital assembly of large structures and habitats, construction of orbital factories for semiconductors and other high-value items, space hotels, and surprisingly, orbital villages with individual or multi-family homes. Over 140,000 people in the U.S. alone have a net worth over 50 million USD, and thousands of these might opt for an orbital home if it could be mass-produced and lofted for ~30 million USD. Humanity can begin colonizing ELEO in the coming decade, and small satellites could provide a rich infrastructure to support it.

INTRODUCTION

The commercial space revolution, sometimes referred to as "New Space," has accelerated our expectations for the development of Earth orbit and beyond. New Space typically leverages and integrates commercially available technologies to provide new space transportation systems and on-orbit services. Prime examples include the SpaceX Falcon 9 launch vehicle family with reusable first stage, their Starlink mega constellation for broadband communications, the ICEYE synthetic aperture radar (SAR) constellation, and the Planet Labs Dove constellation for almost continuous Earth observation at ~4-meter resolution.[1,2,3,4]

The reusable Falcon 9 first stage has already enabled a ~5 X reduction in delivery cost to low Earth Orbit (LEO) for "medium" launch vehicles: 1,900 USD/kg today vs. ~ 10,000 USD/kg between 1990 and 2010.[5] Inexpensive reusable launch vehicles somehow evaded development during the first 50 years of the Space Age. The Wright brothers' first flight of an airplane was in 1903, initiating the modern Age of Flight. We didn't have to wait until 1953 for airplanes that could safely land, refuel, and take off again. Fortunately, SpaceX, Blue Origin, Stoke Space, and others are currently working on reusable first *and* second stages that could provide another significant reduction in delivery cost to orbit.[6,7,8] This airplane-like approach to space transportation where launch hardware is reused tens to hundreds of times before refurbishment will lower launch costs and enable new missions and applications that will further increase launch demand and launch rates. The fully reusable "super heavy" Starship, for example, has been touted by SpaceX founder and CEO Elon Musk to potentially deliver 150,000 kg to LEO for ~10 million USD within 3 years; about $67/kg.[9] Factoring in extra profit for commercial sales, inevitable development delays, and current levels of inflation, I would expect launch costs to LEO between 200 and 300 USD/kg by 2028 using Starship.

Historically, launch vehicle reliability has been more important than delivery cost to orbit for one-of-kind payloads and especially for manned missions. This is where fully reusable launch vehicles excel. Overall flight reliability can be significantly increased by using vehicles that has successfully flown before, and by building flight statistics over thousands of flights with continual upgrading of components and systems as required. The U.S. Space Shuttle had a 98.5% flight success rate based on 135 flights. To date, the Falcon 9 has flown 342 times with only one major failure and one secondary payload delivered to the wrong orbit; a 99.7% success rate for delivering payloads to orbit. The "Full Thrust" v1.2 version has flown 323 times with no failures. This exceptionally high reliability is ideal for manned launch systems, allowing development of commercial space stations and space tourism during the next 3 to 5 years.

Within 5 to 10 years, next-generation fully reusable launch vehicles should further increase the human presence by orders-of-magnitude with potential round trip to LEO prices of about 20,000 USD per 100-kg mass person, plus an extra 200 USD/kg for a ~10-kg mass pressure suit, luggage, and on-orbit consumables.

Penn and Lindley published requirements for a viable space tourism launch system in 2003.[10] Their conclusions were that viable space tourism was enabled with per person round trip costs of ~72,000 USD (~530 USD/kg for 136 kg total mass), with a goal of 15,000 USD. Factoring in inflation since January 2003, that would become ~124,000 USD per round trip (enabling) with a goal of 26,000 USD as of April, 2024.[11] These price points, adjusted for somewhat uncertain future inflation, seem possible by 2030. Their analyses indicated that worldwide flight rates of 1,500 per year (4.1 flights per day) with 100 passengers per flight would be required to enable space tourism with an on-orbit stay, with a goal of 12,000 flights per year or 33 per day. These numbers are many orders-of-magnitude higher than today's norm; during 2023 there were only 6 manned orbital launches worldwide with an average manifest of 3.5 crew members each. They are also many orders-of-magnitude lower than the 36.8 million commercial airline flights during 2023 that occurred within our atmosphere.[12]

Elon Musk hinted that a future fully reusable "Starship 3" version should be able to put 200 metric tons into LEO for 2 to 3 million USD. That would cut costs mentioned above by another 4 to 5X presumably during the mid-2030's; about 10,000 USD for a round-trip package for one person to LEO and ~50 USD/kg to transport two hundred metric ton satellites into LEO. Will small satellites survive? Probably, but they will be bigger and heavier due to a ~40 X reduction in delivery cost to LEO, inside much larger payload fairings. We are in the early stages of a new revolution in space exploration and exploitation.

NASA is preparing for this revolution. "It is NASA's goal to be one of many customers in a robust commercial marketplace in low Earth orbit where in-orbit destinations as well as cargo and crew transportation, are available as services to the agency".[13] The International Space Station will be deorbited in 2030, so new space stations must be lofted during the next 6 years. NASA is currently funding Axion Space, Blue Origin, and Voyager Space to develop commercial space station designs.[14,15] Voyager Space plans on using a single StarShip in ~2028 to launch its StarLab inflatable space station with ~450 m^3 internal pressurized volume; half that of the ISS and 67% larger than the condominium I lived in for over 20 years.[16] Hilton is the hotel partner for Starlab; "Hilton will bring the company's renowned hospitality expertise and experience to support the design and development of crew suites aboard Starlab, helping to reimagine the human experience in space, making extended stays more comfortable."[17] Hotels in LEO are coming. Where should they go?

The ISS is in a near-circular, 51.6° inclination orbit with altitude ranging from 370 to 460 km. The altitude maximizes payload delivery mass (keep it low) while minimizing radiation exposure to astronauts (keep it low) while maintaining an acceptable orbital decay rate due to aerodynamic drag (keep it high). The inclination was chosen to allow the massive (24,000+ kg) Zarya and Zevzda modules built in Russia to be launched using Proton rockets from the Baikonur Cosmodrome in Kazakhstan, located at 45.965° N latitude. Baikonur provides an orbit inclination range of 49° to 99°. The ISS flies over 90% of the inhabited Earth, and most importantly, over significant portions of the United States, Russia, Japan, and Europe. The 51.6° inclination also minimizes radiation effects over high inclination angles between 35° and 90°. I will show this later.

The Sievert (Sv) is the SI unit representing the stochastic health risk of damaging ionizing radiation (ions, x-rays, etc.) roughly equivalent to 1 Gray (Gy) of gamma radiation. An astronaut's total career effective radiation dose during spaceflight, set by NASA, should not exceed 600 millisieverts (mSv).[18] In addition, the short-term dose due to a solar particle event should be less than 250 mSv per event. This represents a risk of lifetime cancer mortality of 18% compared to the baseline astronaut (35 year old female with no space radiation exposure) risk of 15%. Note that the average American has a 21% risk due to excess weight, smoking, inactivity, etc., so the NASA standard seems reasonable. Factor in the historical astronaut death rate due to flight failures of 1% to 2% per flight, and it makes even more sense. As launch vehicle reliability improves to 99.9% or better over time due to reusable launch vehicles, and a larger number of civilians consider space tourism and the opportunity to work and live in space, these radiation limits may have to drop.

Al Globus and Joe Strout studied radiation shielding requirements for long-term (a decade or more) habitats in LEO.[19] Their simulations using OLTARIS, NASA's online radiation computation tool, showed that the lowest radiation environment for inhabitants occurred at near-equatorial inclinations at altitudes below 500-km. A ~20 mSv/yr internal effective dose rate was possible using radiation shielding provided by just the pressure containment vessel. The 20 mSv effective dose rate was deemed acceptable for the general human population based on the International Commission on Radiological Protection (ICRP) Guidance for Occupational Exposure (20 mSv/yr), occupational limits established by the U.S. National Council on Radiation Protection (50 mSv/year), and other guidance. The ICRP recommendation is an average over 5 years with a single year limit of 50 mSv.[20] Deterministic health effects caused by acute tissue damage at high dose rates are measured using physical absorbed dose in Grays (Gy), another SI unit. Globus and Strout used a limit of 6.6 mGy/yr for pregnant women.

Table 1 shows some of their results for 500 km and 600 km equatorial circular orbits with several thicknesses of polyethylene radiation shielding. "These data were calculated for a low solar activity period from June 17, 1977, to June 17, 1978 and are thus conservative." Hydrogen is an excellent shielding material for high energy particles such as Galactic Cosmic Rays (GCRs), and polyethylene is a convenient way to keep hydrogen in solid form. Note that an areal density of 10 kg/m^2 using polyethylene sheet with a mass density of 0.9 gm/cm^3 is 1.1 cm thick. Table 1 shows that the 20 mSv/yr effective dose limit is readily met at 500 km altitude using no shielding, but at 600 km, 50 kg/m^2 shielding would have to be added. The 6.6 mGy/yr physical dose limit requires a few mm thick layer of polyethylene at 500 km altitude, or a 0.3-cm thick aluminum hull, and a 22 cm thickness at 600 km altitude.

Table 1: Effective and Physical dose in 500 km and 600 km circular orbits at 0° inclination as a function of polyethylene shielding density.

Altitude:	500 km		600 km	
Shielding (kg/m^2):	Effective Dose (mSv/yr):	Physical Dose (mGy/yr):	Effective Dose (mSv/yr):	Physical Dose (mGy/yr):
0	17.7	10.2	40.1	1,559
10	17.1	3.6	29.8	101
50	15.3	3.9	19.8	21.8
200	12.0	4.2	13.1	5.3
500	11.9	4.6	12.6	4.9

Globus and Strout also showed that at 500 km with no shielding, effective dose increases slowly with orbit inclination up to ~5° degrees (19.0 mSv/yr), which accelerates beyond that (40.5 mSv/yr at 10°; 148 mSv/yr at 15°) as orbits enter the South Atlantic Anomaly or SAA. Physical dose rates accelerate even faster; 162 mGy/yr at 5°, 1,217 mGy/yr at 10°, and 3,270 mGy/yr at 15°.

For a human habitat in free space outside the Earth's protective magnetosphere, they showed that slightly more than 6000 kg/m^2 of polyethylene shielding (~6.6 meters thick!) is required to meet their effective and physical radiation limits. Equatorial LEO orbits below 600 km altitude provide a relatively safe radiation environment for humans and electronics; an effective incubator where new space technologies and assembly techniques can be developed and refined before moving to higher inclinations and orbits.

OUR PROTECTIVE MAGNETOSPHERE

A simple dipole model of the Earth's magnetosphere is shown in cross section in Fig. 1. The magnetic dipole axis is tilted by 11.5° from the Earth's rotation axis and offset by ~500 km from the Earth's center. The L numbers shown in Fig. 1 are defined by:

$$L = r_o/R_E \quad (1)$$

where r_o is the radius of a field line as it crosses the magnetic equator outside the Earth, and R_E is the Earth's radius (6378 km). Each L line in Fig. 1 represents a particular magnetic field line, which is a 2D slice of a rotationally symmetric magnetic field surface, an *L-shell*. Trapped electrons and protons orbit around these field lines and typically bounce back and forth along these lines. Magnetic field strength within a particular *L*-

shell is weakest where it crosses the magnetic equator and strongest within the Earth. Charged particles either reflect back along a magnetic field line before they hit the Earth's atmosphere, or they will collide with atmospheric molecules and be scattered or neutralized. Earth has an inner Van Allen radiation belt roughly between *L* values of 1.2 and 3 (1,200 to 13,000 km equatorial altitude), and an outer belt that ranges from roughly *L*=3 to *L*=9 (~60,000 km equatorial altitude) composed of trapped electrons and protons.

In practice, the Earth's magnetic field has higher-order terms that distort the ideal dipole shape, and solar wind particles push the magnetic field lines closer to the Earth at *L* values higher than ~3 on the sun-facing side. For this work, I focus on near-equatorial orbits at altitudes below 600 km where the trapped charged particle density is very low; a region inside the inner belt.

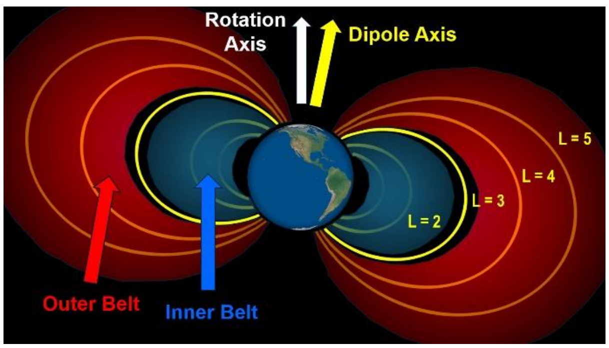

Figure 1: Dipole model of the Earth's magnetic field.

Figure 2 shows the Earth's magnetic field strength at 400 km altitude in heatmap form where red represents the lowest magnetic field strength and dark blue represents the highest field strength. I created this map using data provided by the online World Magnetic Model 2020 calculator for May 9, 2024.[21] Note the red low magnetic field region centered around 20º S latitude and 40º W longitude. This is the SAA where magnetic field lines come closer to the Earth, bringing a part of the inner Van Allen radiation belt down to a few hundred kilometer altitude. The blue regions have the highest field strengths, and these occur near the Earth's magnetic poles.

Single Event Upsets (SEUs), also called Single Event Effects (SEEs), are anomalous conditions in electronic circuits caused by charged particles interacting with individual transistors, diodes, capacitors, etc., fabricated on semiconductor substrates. Changes in logic states resulting from charged particle interactions in memories are one form of SEE. The ionization trail can also temporarily rewire the circuit, possibility forming an electrical short. This "latch-up" event can locally burn out a circuit if local current limiting or control is not employed. If burnout is prevented, the circuit will function normally after a power reset. SEEs and latch-up can also be caused by ionization trails left by Galactic Cosmic Rays (GCRs) traversing semiconductor circuits. GCRs originate outside our solar system and even our Milky Way galaxy.

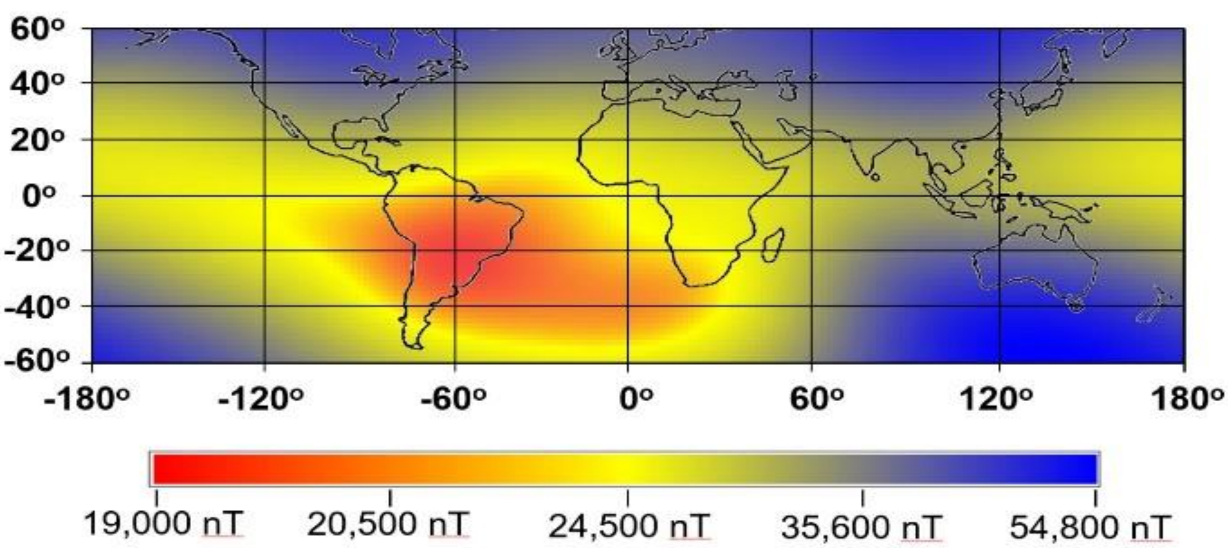

Figure 2. Global heatmap of magnetic field strength at 400 km altitude based on the World Magnetic Model WMM-2020 for May 9, 2024 from Ref. 21. Note that the colormap scale is logarithmic in magnetic field strength.

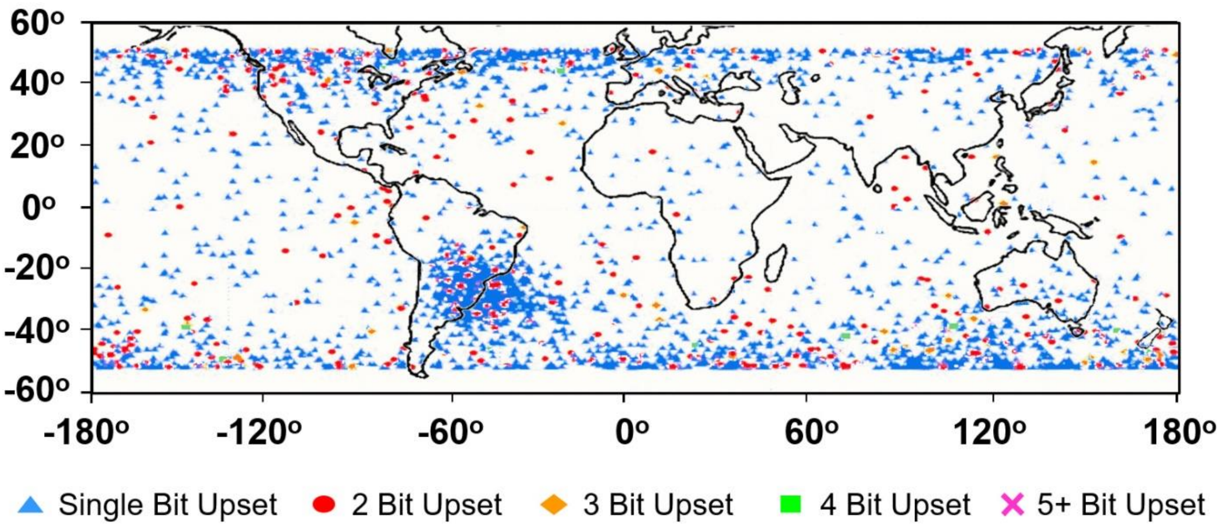

Figure 3. Memory upsets in a 32-megabit DRAM memory module inside the ISS from 11/22/2007 to 7/8/2011. Data from Reference 22.

GCRs are composed of bare atomic nuclei ranging from hydrogen (~89% of total) through uranium with energies ranging from 10 million electron volts (MeV) through 100 billion electron volts (GeV). Galactic cosmic rays bend perpendicular to magnetic field lines. Solar magnetic fields deflect the low energy GCRs so the total GCR flux near Earth is modulated over time; maximum flux tends to occur during solar minimum when solar magnetic fields are low. The Earth's magnetosphere also deflects lower energy GCRs so the flux decreases as one approaches the Earth. The energy spectrum for those that penetrate Earth's field shifts to higher energy since the low energy particles have been deflected away.

Small satellite builders and operators understand that on-orbit particle radiation can generate significant anomalous behavior in commercial, off-the-shelf (COTS) electronics, especially as altitudes increase beyond 1000 km. Figure 3 shows locations of on-orbit SEUs as monitored by a Multiplexer De-Multiplexer (MDM) computer inside the International Space Station (ISS) between 11/22/2007 and 7/8/2011.[22]

A radiation-induced change in one or more bits of a memory word can be detected and typically corrected by implementing Error Detection and Correction (EDAC) hardware or software on a memory module. In this case, the sensor was composed of eight COTS Texas Instruments TMS44400 4-megabit Dynamic Random-Access Memories (DRAMs) with EDAC firmware integrated into the memory refresh cycles.[23] The DRAM was required for normal MDM operation and SEU data were provided by monitoring EDAC operation over time. The ISS was in a 51.6º inclination orbit with altitudes ranging from 350 to 420 km.

Figure 3 shows 2558 single bit upsets, 394 2-bit upsets, 58 3-bit upsets, 11 4-bit upsets, and 20 upsets involving 5 or more bits across the entire 32-megabits of MDM DRAM. This corresponds to 3041 events over 1324 days; about 2.30 events per day. Note that the internal volume of the ISS is typically considered a modest on-orbit environment for COTS electronics.

Figure 3 shows a dense cluster of SEUs within the SAA. These SEUs are primarily due to trapped protons while SEUs outside the SAA, at least within Noth/South latitudes less than 40 degrees, are primarily due to GCRs. Increasing density of SEUs at North/South latitudes above 40º is due to an increasing GCR flux at these latitudes, increased penetration of the inner Van Allen belt to lower altitudes, and an increased amount of time the ISS spends at higher latitudes due to its 51.6º inclined orbit. GCR fluxes increase near the magnetic poles since more of their kinetic energy aligns with the local magnetic field lines, resulting in less magnetic deflection. Van Allen belt particles penetrate closer to the Earth at high latitudes because magnetic field lines approach, and finally enter, the Earth at high latitudes, as shown in Fig. 1. Geomagnetic latitude λ and radius r are related for any L-shell number by:

$$r/R_E = L \cos^2 \lambda. \quad (2)$$

The innermost Van Allen belt particles (L~1.2) with sufficient energy to reach an altitude of 500 km will do so at geomagnetic latitude of 18.6º. Energetic charged articles deeper inside the inner belt at L=2 will reach 500 km at a geomagnetic latitude of 42.8º. To get low radiation levels and low SEU rates, one must keep altitude and orbit inclination low, and avoid the SAA.

SPENVIS Calculations

Globus and Strout were interested in the impact of on-orbit radiation on humans vs. shielding thickness, orbit inclination, and circular orbit altitude. I will focus on the impact of on-orbit radiation on electronics, especially at low altitudes, to map out the lowest radiation environment for testing prototypes and experimental systems based on COTS electronics. I calculated internal dose rate plots for trapped charged particles in LEO using the European Space Agency's Space Environment Information System (SPENVIS). Figure 4 shows internal dose rate plots for multiple orbit inclinations as a function of circular orbit altitude for an aluminum shielding thickness of 1 mm; a minimum shielding thickness for a small satellite like a CubeSat. It is for the period 1/1/2026 to 1/1/2027, uses the AP-8 proton and AE-8 electron models at solar maximum, the CRÈME-96 solar flux model for the worst week, the ESP-PSYCHIC total solar particle fluence model, and the SHIELDOSE-2 ionizing dose model at the center of an aluminum sphere. Figure 5 is for identical conditions, except the aluminum shielding thickness has been reduced to 16 microns to represent ultra-thin membrane spacecraft like the Brane Craft funded by NASA's Innovative Advanced Concepts (NIAC) program.[24,25,26]

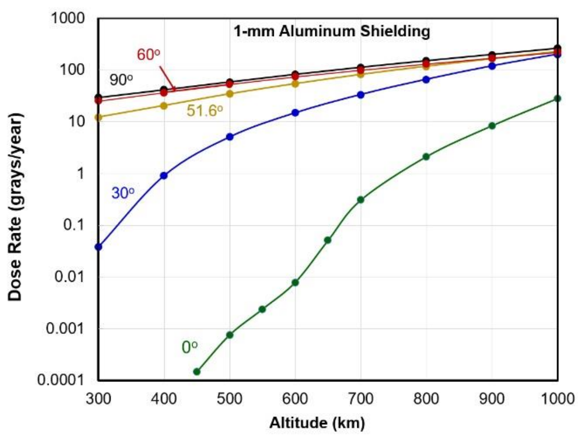

Figure 4. Total dose rate for trapped particles for circular orbits between 300 and 1,000 km in altitude at 0º, 30º, 51.6º, 60º, and 90º inclination inside a 1-mm thick spherical aluminum shield. GCRs not included.

Figure 4 shows a 1 to 4 order-of-magnitude decrease in radiation at 0º inclination compared to 30º inclination from 450 to 1000 km altitude circular orbits. Figure 5 shows an even larger change; 1 to 6 orders-of-magnitude. Figure 6 shows the radiation rates produced by trapped electrons, trapped protons, solar protons, and bremsstrahlung (photons produced within the shielding material generated by charged particles as they slow down) in a 500-km circular orbit at 0º inclination.

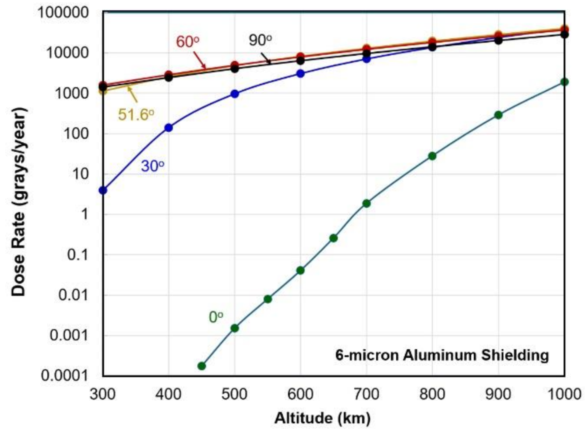

Figure 5. Total dose rate for trapped particles for circular orbits between 300 and 1,000 km in altitude at 0º, 30º, 51.6º, 60º, and 90º inclination inside a 6-micron thick spherical aluminum shield. GCRs not included.

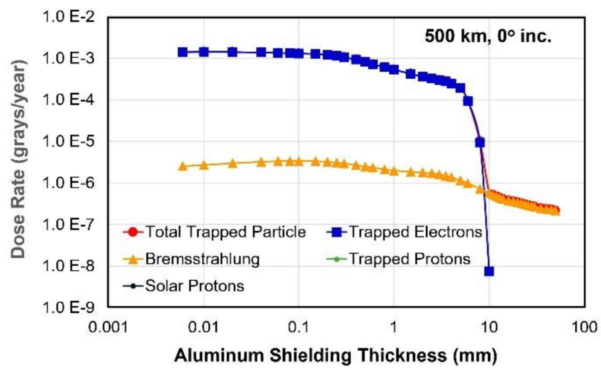

Figure 6. Total dose rate due to trapped particles as a function of aluminum shielding thickness in a 500-km circular orbit at 0º inclination.

There are essentially no trapped protons or solar protons in this orbit in this simulation, which explains the very low dose rate values. Trapped electrons, and bremsstrahlung produced by these electrons as they traverse the aluminum, are the only contributors to radiation damage. Typical COTS silicon-based electronics can withstand total integrated doses of 10 to 100 Grays before failing. GCRs need to be added to complete the picture as far as SEU rates go.

Figure 7 shows a more typical case in LEO, an orbit with the same inclination as the ISS, but at a 450 km constant altitude. In this case, trapped protons and solar protons are present and total radiation dose rates are orders-of-magnitude higher than in Fig. 6. A spacecraft deployed into this orbit with 1-mm aluminum shielding should operate for ~5 months to 4 years using COTS electronics, and longer if the shielding thickness is increased.

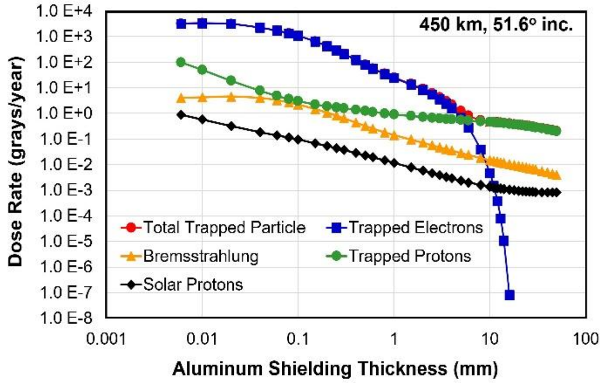

Figure 7. Total dose rate due to trapped particles as a function of aluminum shielding thickness in a 450-km circular orbit at 51.6° inclination.

GCR energy spectra for 0° inclination circular orbits at 350 km, 450 km, 700 km, and 1000 km are shown in Fig. 8, while GCR spectra for 51.6° inclination orbits at the same altitudes are shown in Fig. 9. The equatorial inclination orbits show spectra that are zero up to an energy of ~7,000 MeV, with a rapid increase up to ~10,000 MeV, followed by decline back to zero at higher energies. The lowest energy GCRs have been deflected away by the Earth's magnetic field. The 51.6° inclination orbits show maximum GCR fluxes about an order-of-magnitude higher near 1,700 MeV. These are the lower energy GCRs deflected away at the 0° inclination.

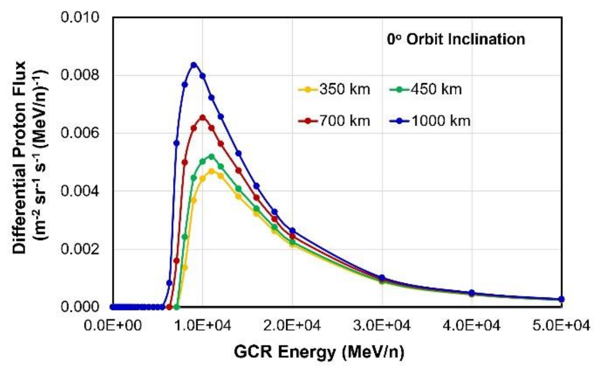

Figure 8. GCR energy spectra for 0° inclination circular orbits at 350 km, 450 km, 700 km, and 1000 km altitude.

Figure 10 shows the effect of inclination angle on GCR penetration in 400 km altitude circular orbits. The 90° inclination has the highest flux GCRs coming in almost parallel to the Earth's magnetic field lines. More and more of the lower energy flux is prevented from reaching 400 km as orbit inclination decreases. Note that there isn't a big difference between 0° and 20° inclinations.

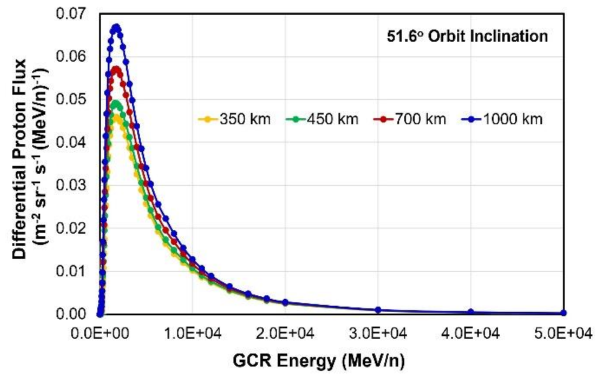

Figure 9. GCR energy spectra for 51.6° inclination circular orbits at 350 km, 450 km, 700 km, and 1000 km altitude.

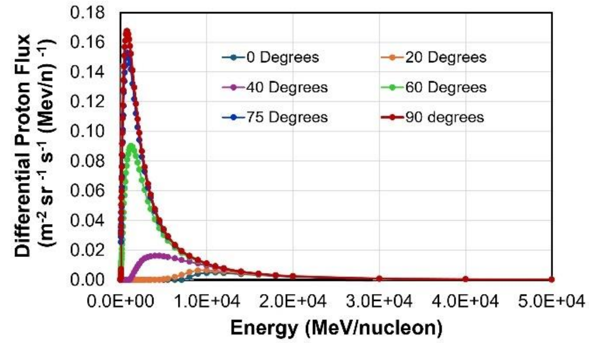

Figure 10. GCR energy spectra in a 400 km altitude circular orbit for orbit inclinations of 0°, 20°, 40°, 60°, 75°, and 90°.

Equatorial orbits below 600 km altitude provide exceptionally low external and internal radiation levels. The 1 mGy/yr trapped particle dose rate inside a 1-mm thick aluminum shield at 0° inclination and 500 km altitude (see Fig. 4) could theoretically provide a thousand years of operation before a total integrated dose of 10 Grays is reached; this is typically the lower COTS TID limit, although some devices, particularly Flash RAM, may begin failing at ~5 Grays. At 30° inclination, the 10 Gray dose limit will occur after only 2 years.

While COTS electronics should not suffer total dose issues in 500 km and lower equatorial orbits, SEUs will still occur due to GCRs. I used the long-term SEU rate calculator in SPENVIS to determine upset rates for a random device (a Micron Technologies 16 Mbit, 3.3 V DRAM from their online library, a legacy part) using SRIM2008 data for the silicon substrate and the CRÈME model with constant linear energy transfer (LET). Figures 11 through 14 show calculated estimated SEU rates in circular orbits as a function of orbit inclination for various aluminum shielding thicknesses at 350 km, 400 km, 500 km, and 600 km altitudes.

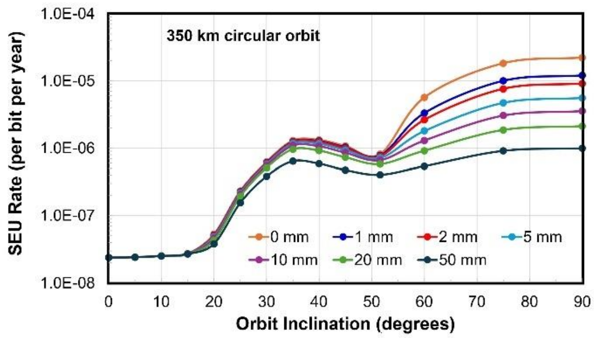

Figure 11. Calculated SEU rates for a Micron 16 Mbit, 3.3 V DRAM as a function of orbit inclination for a 350-km altitude circular orbit for multiple thicknesses of aluminum shielding.

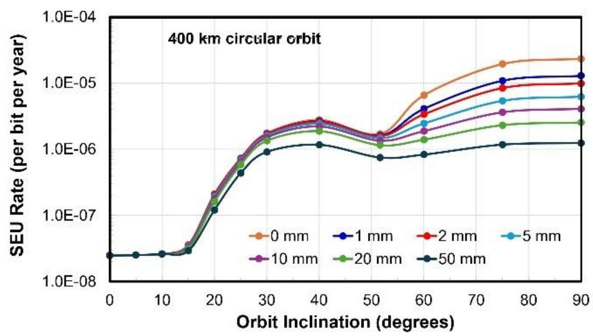

Figure 12. Calculated SEU rates for a Micron 16 Mbit, 3.3 V DRAM as a function of orbit inclination for a 400-km altitude circular orbit for multiple thicknesses of aluminum shielding.

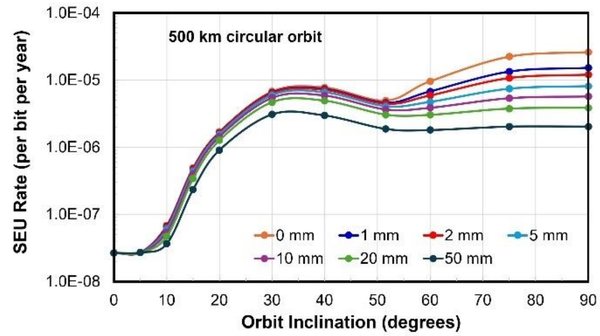

Figure 13. Calculated SEU rates for a Micron 16 Mbit, 3.3 V DRAM as a function of orbit inclination for a 500-km altitude circular orbit for multiple thicknesses of aluminum shielding.

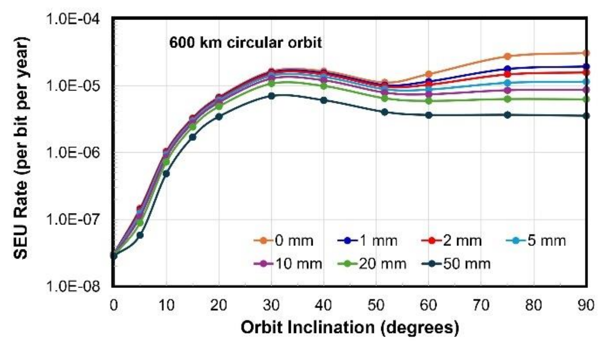

Figure 14. Calculated SEU rates for a Micron Technologies 16 Mbit, 3.3 V DRAM as a function of orbit inclination for a 600-km altitude circular orbit for multiple thicknesses of aluminum shielding.

While different electronic devices will have different SEU rates under the same environment, it is useful to see the general behavior as a function of orbit inclination and altitude. Figure 11 shows the lowest overall SEU rates due to the low 350-km altitude. At 0° inclination, the rate is 2.39 x 10^{-8} per bit per year. This device has 16 Mbits, so the probability of a single SEU event during a year is 40%. Note that the SEU rate changes little for inclinations from 0° to 15° and is almost independent of shielding thickness. This is presumably due to GCRs; the reduced number of GCRs that reach this altitude and inclination are "hard" (skewed towards higher energies; see Fig. 10) at 5 GeV and up. These energies easily traverse aluminum and other shield materials at these modest thicknesses.

The SEU rate increases by 2 orders-of-magnitude between 15° and 35° inclination, and shielding thickness becomes more effective. This is due to orbits entering more of the SAA as inclination increases. Trapped charged particles begin to dominate SEU rates. At higher inclinations, SEU rates locally peak at ~40° and then drop as inclination increases to roughly the ISS orbit value (51.6°). This is due to less time spent in the SAA, and less time spent within latitudes where trapped particles exist. GCR fluxes, however, are increasing. Trapped particle fluxes drop significantly above ~52° inclination while GCR particle flux increases, with more particles at lower energies. This results in the highest SEU rates with a plateau between 75° and 90°. This is where GCRs dominate, especially the low energy particles that interact more strongly with shielding.

Figures 11 through 14 show that the range of orbit inclinations with minimum SEU rates for this device (below 3 x 10^{-8} per bit per year) decrease as altitude increases. Orbit inclinations up to 20° are acceptable for circular orbits at 350-km altitude, up to 16° inclinations are acceptable at 400-km altitude, up to 6° inclinations are acceptable at 500-km altitude, and by 600-km altitude no inclination is acceptable. This orbital volume has the lowest radiation levels in the inner solar system.

ELEO: THE ORBITAL INCUBATOR

The previous section showed that LEO orbits roughly within the green shaded altitude/inclination area shown in Fig 15 provide the lowest on-orbit radiation levels. SEU rates are 1.5 to 2.5 orders-of-magnitude lower than those at more typical orbital inclinations, e.g., 45° and higher, with shielding thickness of a few mm or less. This is where students, agencies, and companies should first test their new space designs, if possible.

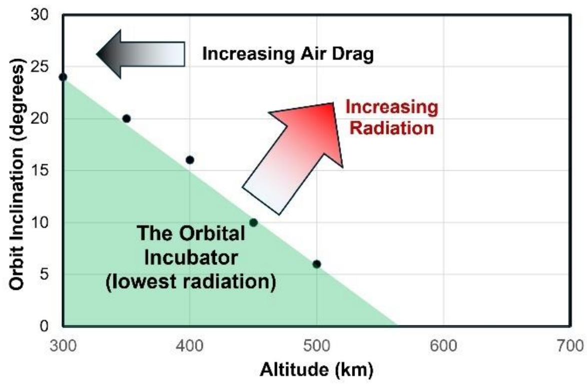

Figure 15. Orbit altitude/inclination map of the Orbital Incubator where trapped protons are almost nonexistant.

The advantages of ELEO incubator orbits are:

• A single equatorial ground station can access an ELEO satellite once per orbit, every orbit.

• Inexpensive terrestrial solar cells can be used; no need for radiation-hardening cells and cover glasses.

• Magnetic attitude control is simplified; the local magnetic field is fairly constant and parallel to the Earth's surface.

• An equatorial launch site will maximize the rotational surface velocity, thus reducing the required ΔV to get to orbit and thus maximizing payload mass.

• Sunlight/eclipse cycles are almost constant with no full sunlight orbits to cause overheating.

• Optimum geometry for orbit raising/lowering using a gravity-gradient stabilized electrodynamic tether.

• Passive aerodynamic drag can bring down small satellites within months.

• The reduced radiation environment causes fewer pixel anomalies in imaging arrays.

• The reduced radiation environment reduces optical fiber degradation in fiberoptic gyros and fiber amplifiers for optical communications.

• Standard CMOS electronics can function outside the spacecraft; no need for radiation-hardening.

Active membrane spacecraft

The last bullet above enables active membrane spacecraft like the Brane Craft (see ref. 24 - 26) to function without radiation-hardened electronics. These spacecraft have one or more spacecraft systems fabricated as thin-film structures deposited on large-area membranes like solar sails. A *Brane Craft* is an active-mem***Brane*** space***Craft*** with solar cells, power conditioning, command and control electronics, communications systems, antennas, propulsion systems, attitude and proximity sensors, and shape control actuators fabricated on ~10-micron-thick Kapton® sheets. Traditional spacecraft systems are typically composed of multiple three-dimensional components that are integrated together on one or more printed circuit boards (PCBs) and electrically-connected to other spacecraft systems using wiring harnesses and associated connectors. One or more spacecraft systems are then integrated together in a box that provides mechanical support, electromagnetic shielding, passive thermal control, and space radiation shielding. Active membrane spacecraft eliminate the boxes and PCBs to reduce mass by at least two orders-of-magnitude for a given surface area. Surface area is established by analyzing mission-specific requirements for solar power generation, heat rejection, antenna gain requirements, and sensor area requirements.

Figure 16 shows an artist's concept of a Brane Craft design for active orbital debris removal throughout LEO, from 200 to 2000 km in altitude, that is about to envelop a piece of orbital debris. This design uses integrated nano-electrospray thrusters operating at 4000 s specific impulse (I_{sp}) for propulsion and basic attitude control, with a total delta-V (ΔV) of 16 km/s (that's not a typo). Due to a low wet mass of 81 grams ("wet" means loaded with propellant) with a maximum thruster system power level of 180-W, this electrically propelled spacecraft can accelerate at an unprecedented 0.1 m/s^2 and consume all propellant in a matter of days. Spacecraft electronics, thin film solar cells, and surface-warping microactuators would be fabricated directly on the Kapton® sheets. Surface warping was required to give this thin-film design structural rigidity and the ability to point different parts of the spacecraft independently. The major issues were sunlight/eclipse thermal control, the need for 50 kilogray hardened electronics due to shielding of only tens of microns at 2000-km altitudes, and micrometeorite damage. In the ELEO incubator, this and related designs would not need radiation hardening.

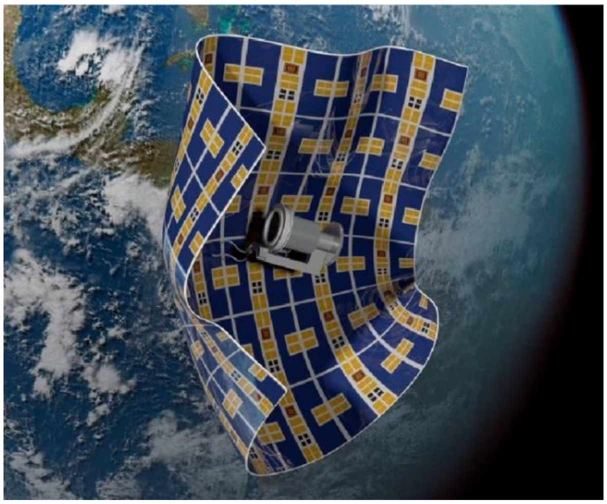

Figure 16. Artist's concept of a Brane Craft for active orbital debris removal. Image from ref. 26.

There are many potential applications of active membrane spacecraft, or traditional spacecraft with active membrane appendages, in the orbital incubator:

• Rapid delivery of kg-class parcels between spacecraft and platforms within an expanded ELEO envelope extending outwards to 750 km altitude and 20 degree inclination.

• Low mass, low-cost solar power stations in ELEO for power beaming to other spacecraft plus ground, air, and sea platforms near the Earth's equator. Ten stations equally distributed across a 0^o inclination; 500-km altitude orbit could continuously power a terrestrial platform. Note that terrestrial solar cells cost about 0.5 USD/W, compared to hundreds of USD/Watt for triple-junction space-rated cells.

• Sunshades; aluminized Kapton® disks to reflect solar radiation away from the planet to counter climate change. Putting them in ELEO is far cheaper than deploying them at the Earth-Sun L-1 point where each shade would be used continuously.[27]

The ELEO incubator can also be used to prepare for the next revolution: human settlement of LEO.

ELEO: FROM INCUBATOR TO NURSERY

The introduction section discussed low transport to orbit costs coming in the next decade due to the development of fully reusable space transportation systems, the rise of commercial space stations in the near term, and the work by Globus and Strout in showing that we should probably operate these stations at low orbital inclinations and altitudes; ideally at 500 km or less at 0^o inclination. Higher orbital inclinations may provide more planetary coverage, but we already have constellations of small satellites for that. On-orbit research generally exploits microgravity and/or high vacuum, which are independent of orbit inclination. Why subject civilian workers to unnecessary radiation and the owners to potential radiation-based lawsuits?

The ELEO Incubator provides a great environment to support the first wave of civilian endeavors in space. Additional benefits of the 0^o inclination ELEO orbit are:

• Launch windows to an ELEO platform from an equatorial launch site would occur once every 93 to 97 minutes; no need to wait for orbital precession.

• The ΔV to go from one circular orbit to another at the same orbital inclination within an altitude range of 300 to 600 km is low. An impulsive transfer from 300 km to 600 km, for example, requires 168 m/s. Going from 400 km to 500 km requires only 56 m/s.

A decade from now, transport of 150,00 to 200,000 kg to LEO could cost about 10 million USD. This price facilitates:

• Orbital assembly of large structures and habitats like Kaplana II, a cylindrical habitat of ~100 meter diameter, a mass of ~16.8 million kg, and a cost of roughly 4 billion USD.[28] With 400+ condominiums, each condominium could sell for 10 million USD. The Kaplana II design was proposed by Marotta and Globus in 2018.[29] Note that the 4 billion USD Kaplana II construction cost is the same as that for rebuilding One World Trade Center in New York.

• Construction of orbital factories for semiconductors and other high value density (USD/kg) items by 2050.[30] LEO provides "free" ultra-high vacuum, microgravity, easy disposal of hazardous materials like arsenic compounds without impacting the terrestrial environment, and direct access to "green" solar power.

• "The Cloud above the clouds": Data processing centers, most likely including some form of artificial intelligence, to support terrestrial and orbital users. ELEO provides the lowest-radiation and lowest SEU rates in orbit.

• Commercial space stations and space hotels.

• Orbital homes; tomorrow's version of a 60-meter super yacht.

Over 123,000 people in the U.S., 32,00 in China, 9,000 in Germany, and 5,000 in India had a net worth over 50 million USD in 2022, and thousands of these might opt for an orbital home in the future if it could be mass-produced and lofted for ~30 million USD.[31] Can a home-like space station be built for 20 million USD and delivered for an extra 10 million? Certainly not today but it should become possible through free enterprise, competition, access to environmental testing facilities, and mass production. In 2014, Bigelow Aerospace offered the BA-330, a 330 m^3, 25,000 kg mass inflatable space station for 6 people for 125 million USD.[32] A factor of 5 to 10 reduction in price is possible if they were to make hundreds of units per year since non-recurring research and development costs dominate new space hardware production. Unfortunately, Bigelow Aerospace has gotten out of the space station business, but newcomers like Sierra Space and VAST have entered.[33,34]

These space stations are "home" sized. Rather than design, build, test, and fly, and finally occupy a large ELEO settlement capable of supporting hundreds of occupants, it may be easier to use the small satellite approach: go small, reduce fabrication, testing, and launch costs, rapidly evolve technology using on-orbit testing, and utilize constellations instead of a single large spacecraft. Civilian space stations could quickly evolve into homes that become elements of an orbital village with hundreds of inhabitants.

CONCLUSIONS

Equatorial Low Earth Orbit (ELEO) below 500 km has an exceptionally low space radiation environment that is ideal for testing new spacecraft designs and electronics. This Orbital Incubator ranges from 0º to 24º inclination at 300 km attitude to 0º inclination at ~550 km altitude. Others have shown that a 0º inclination, 500-km altitude orbit requires no extra radiation shielding mass to support long-term space settlements. With a continuing reduction in transportation cost to LEO by exploiting fully reusable systems, Humanity should begin colonizing ELEO in the coming decade, turning the Incubator into a Nursery. Within a decade, it should be possible for thousands of high-net-worth individuals to buy their own orbiting home for the cost of a 60-meter super yacht. Small satellites could provide rich infrastructure services like parcel delivery, waste disposal, beamed power and communications, intra-orbital taxi services, etc. to new communities in space. Instead of going the "megasatellite" route, space habitats could use the small satellite approach that reduces research, development, and testing costs by building smaller spacecraft, and rapidly evolving designs through on-orbit testing and rapid turn-around times between redesign and getting flight data. We should use an "orbital village" of home-sized space stations to raise Humanity into space.

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