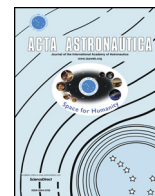




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The edge of space: Revisiting the Karman Line

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ABSTRACT

In this paper I revisit proposed definitions of the boundary between the Earth's atmosphere and outer space, considering orbital and suborbital trajectories used by space vehicles. In particular, I investigate the inner edge of outer space from historical, physical and technological viewpoints and propose 80 km as a more appropriate boundary than the currently popular 100 km Von Kármán line.

1. The edge of space

1.1. Introduction

The argument about where the atmosphere ends and space begins predates the launch of the first Sputnik (e.g. Ref. [1]). The most widely - but not universally - accepted boundary is the so-called Karman Line, nowadays usually set to be 100 km altitude, but boundaries ranging from 30 km to 1.5 million km have been suggested, as summarized in a 1996 book by Goedhart [2].

Although the subject has not been much addressed in the physics literature, there is an extensive law/policy literature on the subject - see e.g. Ref. [3-7]. Hansen [7] notes that COPUOS has wrestled with the issue continuously since 1966 (Ref. [8]) without a conclusion. COPUOS, the Committee on Peaceful Uses Of Outer Space, was established in 1959 and is the UN body dealing with astronautics. In COPUOS the USSR repeatedly proposed either 100 or 110 km but the US rejected any definition.

As early as 1957 Robert Jastrow ([1], cited in Ref. [6]) suggested that the air space boundary should be at 100 km. Goedhart (p. 3) lists almost 30 different proposals from the 1951–1962 period for an altitude boundary ranging from 20 to 400 km; most values are in the 75–100 km range. A number of these authors suggest that the large variations with time of atmospheric properties make it futile to locate a true boundary of space based on physical arguments. In this paper I will argue the contrary: there is a moderately-well-defined boundary of space, it coincides with the Karman line as originally defined, and that line is close to 80 km, not 100 km.

1.2. The functionalist objection

There have been objections (particularly in the United States) to defining any *legal* boundary of space on the grounds that it could cause disputes about airspace violations below the boundary, or that too high a boundary could inhibit future space activities. Those advocating this position, beginning with McDougal and Lipson [9], are sometimes referred to as 'functionalists' (see also [5,6]). The functionalist approach would ensure that long range ballistic missiles were not made subject to international agreements on 'space objects', which may explain part of its appeal to the US establishment.

The general tenor of these objections, however, seem applicable to any law about anything. Functionalists also suggest that space law would apply to an orbital rocket even while it was within the atmosphere, or possibly on the ground. This seems unnecessary as national and international law would already apply. Suggestions that the purpose of a vehicle, not its location, should determine the legal regime may be appropriate for questions of licensing, but will not help if a vehicle classified as belonging to one regime collides or interferes with one from another regime.

The special need for distinct laws specifically for space (and thus the need for legal definition of space) arises from:

- The lack of national boundaries in space (analogous to international waters)
- Objects in space may remain in motion relative to the Earth for long periods of time (depending on the orbit, from days to millenia) without the need to refuel or land.
- The large area swept out by a space object in a given time due to the

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large kinetic energies involved in space travel, meaning that a given space activity will extend over a wide area rather than be spatially localized as most Earth-based activities are.

- The high destructive potential of collisions, since their effects also are felt over a wide area.

The latter two considerations in particular are specific to the region above the atmosphere where orbital dynamics dominate, although they do not apply to activities on the surfaces or in the atmospheres of other worlds such as the Moon or Mars.

In any case, my main interest here is to define a boundary of space for the use of historians of spaceflight, rather than to define a legal regime, so I will give no further consideration to the functionalist view. To answer questions such as ‘how many astronauts have flown in space?’ or ‘how many European Space Agency rockets have reached space?’, we need to adopt a definition of space, even if it is not a legal one. I do not argue that there needs to be a single definition of ‘space’ that applies in all contexts. Physicists, lawyers and historians may need a boundary of space for different purposes and to address different questions; the ‘edge of space’ might be defined differently in different international fora. Nevertheless it is useful for those definitions to be based on a common and accurate understanding of the physical conditions at the air-space boundary, and I hope that this article can make a positive contribution in that respect.

1.3. McDowell (1994) proposal

Milt Thompson's book [10] talks about his flights in the X-15 rocketplane to the ‘edge of space’. In my Quest article ‘The X-15 Spaceplane’ [11] I discussed this term and concluded that the correct choice for the edge was 80 km, not 100 km. The discussion is repeated and expanded in this paper. In part, I argued:

In the late 1950s the USAF decided to award ‘astronaut wings’ to pilots flying above 50 statute miles. This boundary was chosen as a nice round figure, but I want to argue that it is also the right choice from a physical point of view it seems natural to choose the outermost [physical atmospheric] boundary, the mesopause, as the physical boundary which marks the edge of space. It turns out that the traditional value for the height of the mesopause, 80 km, is also within 500 m of the 50 mile ‘astronaut wings’ boundary historically used by the USAF. I therefore suggest that we adopt as the formal boundary of space an altitude of exactly 80 km, representing the typical location of the mesopause.

In this paper I expand on the arguments in my 1994 article. All references to altitudes are intended to represent geodetic height (height above reference ellipsoid); I ignore local topography. Note that in some astronomical contexts use is made of a ‘geocentric’ height relative to a fictional spherical Earth, which may differ by of order 10 km.

2. Cultural arguments: historical definitions of the edge of space

In recent decades the 100 km Karman line has gained ascendancy as the most commonly used boundary, notably for the Ansari X-Prize won by the Spaceship One team.

The ‘official’ status of the von Karman line, such as it is, comes from the undated paper ‘100 km Altitude Boundary For Astronautics’ [12] on the web site of the Astronautics Records Commission (ICARE) of the Fédération Aéronautique Internationale (FAI), which certifies world records for aeronautics and astronautics. It is unfortunate that discussion in this official document in the section ‘demonstration of usefulness of Karman line’ appears to be poorly researched:

In the early 1960s the U.S. X-15 Aircraft was flown up to 108 km. In that part of the flight it was really a free falling rocket, with no aerodynamic control possible. In fact, it was considered an astronomical flight, and the pilot got, as a consequence, his astronomical wings, i.e. the

recognition of being an astronaut.

This is not incorrect, but the USAF considered all X-15 flights above 80 km as astronomical flights and gave those pilots astronaut wings. So this paragraph would argue for 80 km, not 100 km. The first non-NASA pilot to be awarded astronaut wings was X-15 pilot R. White, as described in Life Magazine (Aug 3 1962):

Major Bob White of the US Air Force is the nation's newest space hero. [...] He has [...] a brand-new award on his chest that makes him a member of the nation's most exclusive club. It was a special set of pilot's wings that signified he had flown higher than 50 miles above the earth and thereby had qualified as a spaceman.

White flew to 95 km on 1962 Jul 17. If a limit of 100 km instead of 80 km is used, White, Robert Rushworth, Jack McKay, Bill Dana and Mike Adams lose their space traveler status (Joe Engle keeps his because he later flew on Shuttle, and Joe Walker passed the Karman line on his X-15 flights).

In the past few years, even lower values have been proposed. The prominent astrophysicist Alan Stern has argued (personal communication) for balloon altitudes in the 30–35 km range as being ‘space’ or ‘near space’; Stern is involved in the World View high-altitude-balloon near-space tourism venture.

3. Physical boundaries in the atmosphere

3.1. Atmospheric layers: the mesopause as a proposed boundary

As you leave the surface of the Earth and ascend into the atmosphere, it gets colder - until you pass a boundary at which the temperature begins to increase again. There are several such reversals in temperature gradient and the traditional definition of atmospheric layers uses them to define the layers of the atmosphere as ‘-spheres’ with boundaries called ‘-pauses’ [13]:

- The troposphere, between the ground and the tropopause
- The stratosphere, between the tropopause and the stratopause (about 50 km)
- The mesosphere, between the stratopause and the mesopause (about 85–90 km). Here CO₂ cooling dominates solar heating.
- The thermosphere, between the mesopause and the exobase (about 85–500 km, variable). In the thermosphere the physical state is dominated by absorption of solar radiation; the resulting ionized atoms have their own behaviour and the composition of the atmosphere departs from the N₂/O₂ mix of the lower layers. The thermosphere region overlaps (but has a definition which is not quite the same as) the ionosphere, the region where ionized particles dominate the physics. It includes the LEO region where the ISS orbits.
- The exosphere, beyond the exobase. Here the density is so low that the atoms don't act like a gas.

Another relevant boundary is the turbopause, below which all the different molecules have the same temperature, and above which they behave independently; below the turbopause you are in the ‘homosphere’ where everything is mixed; above it is the ‘heterosphere’ where everything acts independently. The turbopause is at about 100–120 km. In 2009, press releases referencing a paper by Sangalli et al. [14] about the Joule II rocket mission trumpeted a measurement of the ‘edge of space’ at 118 km. This was actually the height at which the motion of charged atoms (ions) becomes dominated by the electromagnetic field rather than by winds in the neutral atmosphere; it is likely a function of time and location and so their value for 2007 Alaska should not be taken as a generic result.

The chemical composition of the atmosphere is largely constant up to the mesopause. From a physical point of view, it is therefore

reasonable to think of the atmosphere proper as including the troposphere and stratosphere and (with some qualification) the mesosphere, and identifying the thermosphere and exosphere with the common idea of ‘outer space’. Either the mesopause or the turbopause are reasonable choices for a boundary, as the outermost physical atmospheric boundaries below the region where most satellites orbit. It is true that each of these definitions varies in height by 10 km or more depending on solar activity, upper atmosphere dynamics and other factors. The 1976 US Standard Atmosphere value for the mesopause is a constant 86 km; Xu et al. [15] used observations with the SABER radiometer on the TIMED satellite to study variations in the mesosphere altitude. Their data suggest a mesosphere altitude of 97 ± 2 km for equatorial and winter polar regions and 86 ± 2 km for summer polar regions; these values are higher than I had assumed in my 1994 discussion.

A reasonable alternative air/space boundary would be the base of the mesosphere instead of its ceiling; or, one may consider the mesosphere as neither air nor space. In 1976 Reijnen [16] and Jager and Reijnen [17] introduced the idea of ‘mesospace’ as an intermediate legal regime between airspace and outer space; the mesosphere is a natural candidate for mesospace. Oduntan [18] suggested a buffer zone from 55 to 100 miles (88–160 km), apparently partly based on the existing incorrect estimates of 150 km as the lowest orbital perigee. In fact, as shown below, 55–100 km would be a more suitable choice. Pelton [19] has coined the term ‘protospace’ or ‘the protozone’ for the intermediate region, which he defines as the 21–160 km range. In general, however, the idea of mesospace has not yet gained general acceptance.

3.2. Outer limits of the atmosphere and boundaries in deep space

The true outer edge to the Earth’s atmosphere, or a reasonable candidate for it, is the magnetic shock front with the solar wind. The magnetopause boundary forms a comet-shaped region, typically around the height of geostationary orbit on the sunward side of Earth and extending out to beyond the Earth-Sun L2 point. One can also consider the gravitational boundary of the Earth-Moon system with respect to the Sun, conventionally chosen to be the 1.5-million-km radius Hill sphere marked by the Earth-Sun Lagrange points L1 and L2. While material within the magnetosphere and/or the Hill sphere could be considered part of the Earth’s outer atmosphere, few would argue that this region is not ‘space’. Rather, these boundaries may be used to distinguish space in the Earth-Moon system from interplanetary space.

Indeed, one may usefully identify a number of different conventional regions in the region of space humans and their robots have explored, listed here for convenience of reference.

- The boundary between Low Earth Orbit (LEO) and Medium Earth Orbit (MEO), is sometimes taken to be a 2 h orbital period, which corresponds to an altitude of 1682 km for equatorial orbits, but nowadays a round value of 2000 km is relatively standard, e.g. Ref. [20].
- The geosynchronous altitude, 35786 km above the equator [21].
- The Earth-Moon 1:4 resonance altitude EL1:4, 145688 km altitude. I introduce here this boundary between ‘near-Earth space’, where the effects of lunisolar perturbations are minor and a simple Keplerian elliptical satellite orbit is a reasonable approximation and ‘deep space’, which I take to include both distant Earth satellite orbits (such as that of the TESS satellite launched in 2018) and lunar and planetary missions. For Earth satellite orbits in ‘deep space’ the lunar perturbations are large enough to make big changes in the orbital elements on month-long timescales. As a practical matter, NORAD/JFSCC systematically monitor orbits of near-Earth space spacecraft but do not attempt to monitor deep-space Earth satellite orbits in a comprehensive way - this is left to astronomers who accidentally pick up satellites in such orbits while searching for asteroids. As will all these boundaries, one could reasonably make a

different choice here - a round altitude of 100,000 km, or a different resonance like EL1:3. I propose EL1:4 by analogy with the Sun-Jupiter 1:4 resonance that is conventionally taken to mark the inner edge of the asteroid belt (and thus the point inside which solar orbiting objects can be considered as not strongly perturbed by Jupiter).

- The Hill Sphere [22], bounded by the Earth-Sun Lagrange points, with a radius of 1.496 million km. This is the conventional boundary between considering objects as orbiting Earth but perturbed by the Sun, and considering objects as orbiting the Sun but (if close to the boundary) perturbed by the Earth. Another choice here is the so-called ‘gravitational sphere of influence’ or Laplace sphere [23], which is at approximately 929,000 km radius; it is used in the method of patched conics. In general the Hill sphere, which takes into account the orbital angular momentum, better reflects the effective boundary at which orbiting objects may be captured by or escape from the Earth-Moon system (e.g. Refs. [24] [25]).
- The ν_6 secular Sun-Jupiter-Saturn resonance which marks the conventional inner edge of the asteroid belt at 2.06 astronomical units (308 million km) from the Sun [26]; it coincides with the 1:4 Sun-Jupiter resonance [27] and asteroid orbits near this resonance are unstable, soon perturbed to enter the inner solar system. Although there is no generally agreed definition, this location is a reasonable place to mark as the boundary between the inner and outer solar system.
- The outer edge of the Solar System itself is controversial. Plasma physicists associated with studies by the Voyager probes have made various estimates of the ‘heliopause’ boundary between the solar wind and the broader-scale flow of interstellar gas, for example at 121.7 astronomical units (1.8×10^{10} km) [28]. However, dynamical astronomers would point out that objects remain gravitationally bound to the Sun much further out [29], of order 200,000 astronomical units (3×10^{13} km).

4. Technological boundaries at the edge of space

4.1. The highest vehicles using aerodynamic lift

On 1973 Jul 25 a modified Mig-25 designated the Ye-266 reached 36.2 km, and on 1977 Aug 31 a Ye-266 M reached 37.65 km. These altitude records for non-rocket-powered airplanes were set at the Soviet LII Gromov flight test center by test pilot Aleksandr Fedotov [30]; they involved brief arcs to high altitude. The highest steadily flying non-rocket plane was the remotely piloted Helios, which reached 29 km on 2001 Aug 14. The highest crewed balloon reached 34.6 km in 1961. However, uncrewed scientific research balloons reach over 40 km on a routine basis. A 1972 record of 51.8 km was exceeded in 2002 by the 54-m-diameter BU60-1 balloon from the Japanese ISAS team, which reached an altitude of 53 km [31]. Despite the then-stated intent of the ISAS team to reach 60 km, it appears that the technological limiting ceiling of vehicles which require the atmosphere for lift is close to the stratopause at 50 km. This sets a sensible lower limit for the boundary of space.

4.2. The lowest quasi-circular orbits

The much-cited FAI article [12] about the Karman line continues:

Later in the same decade (or very early in the next; Soviet information at the time was very scanty) the Soviet Union put in orbit an unmanned satellite, in very low orbit, whose attitude was controlled by aerodynamic forces. The real reason of such an experiment is not yet known. It is known however that it successfully described a few orbits just above the 100 km line (how much higher I do not know), but collapsed rapidly shortly after he crossed, or got too much close to, the 100 km. Karman line.

Soviet information was not that scanty even at the time; the author is clearly referring to the well known Kosmos-149 satellite, which carried an extendable structure used to stabilize it along the velocity vector. This satellite, whose then-classified name was DS-MO No. 1, was launched into a 245×285 km orbit, low enough for the drag stabilization to work but much higher than needed to avoid catastrophic decay. It remained in orbit from 1967 Mar 21 to Apr 7. The last US orbital data was on Apr 5, at which time it was in a 201 km circular orbit. But there are many well documented cases of even lower altitude satellites. Since the idea that 200 km is the low boundary for satellite orbits is so widespread, I consider here a number of counterexamples.

In May 1976, the satellite GAMBIT Mission 4346 (1976-27 A, US National Reconnaissance Office) was tracked in an orbit with a perigee between 125 and 135 km for a full month; this is not unusual for this kind of satellite, which performs frequent rocket burns to counteract decay. Its apogee was around 350 km. Empty rocket stages are frequently left in low orbits of under 200 km and reenter after several days; the final tracked orbit is often between 130 and 140 km.

From 2016 Aug 16–19, China's Lixing-1 satellite operated in a near-circular orbit of 124×133 km for three days prior to reentry; this is the lowest circular orbit ever sustained for multiple days.

In contrast, when the Space Shuttle lowered its perigee to 50 km as part of the deorbit burn, it reenters within an orbit. Shuttle external tanks, discarded at orbit insertion, often had perigees around 70–75 km and in all cases did not complete their first orbit.

Based on circular orbit data, 125 km is a conservative upper limit for the beginning of space.

4.3. The lowest perigees for elliptical orbits

A satellite in an elliptical orbit can survive a brief periapsis passage at lower altitudes than the extended exposure of a circular orbit would permit. Below I give examples of low perigee elliptical orbit satellites. The air density increases rapidly, and so there is a limit below which even a highly elliptical orbit satellite will be rapidly destroyed. This limit turns out to be in the 80–90 km range except in very special cases.

Consider a satellite in an elliptical orbit whose perigee is around 80 km. Are we to say that it is in space only for the higher parts of its orbit, and that, for example, space law stops applying to it at each perigee passage? The repetitive nature of an orbit makes this case different from the one-off transition from the space to aviation environment during launch or reentry. I therefore conclude that attempts to use 'lowest circular orbit' to define the space boundary are fundamentally misguided, and 'lowest sustainable perigee' (for more than two revolutions, say, of an elliptical orbit) is a more appropriate criterion.

Before considering specific examples, a detailed discussion of the pitfalls in satellite perigee height calculations is warranted.

The Earth satellite catalog in widespread use is that currently maintained by the US military, since the corresponding Russian catalog is not publicly available and other sources (e.g. those from hobbyists) are relatively incomplete. The catalog was begun in 1957 by the Smithsonian Astrophysical Observatory [32]. The North American Air Defense Command (NORAD) collaborated with SAO and ultimately took over the catalog. Orbital data here and below are obtained from the Two-Line Orbital Elements (TLE) issued by the US Joint Space Force Component Command [33], the current inheritor of NORAD's space tracking responsibilities. For each satellite, there may be several orbit determinations ('element sets', 'TLE sets' or simply 'TLEs') per day. These data have been federated with spacecraft historical information from the author's catalog of satellites [34].

The TLEs provide mean motion and eccentricity of a fitted time-averaged orbit, the 'SGP4 mean elements' [35], [36]. It is common practice (notably in the official public satellite catalog on space-track.org, or historically in the RAE Table Of Earth Satellites and reports derived from it) to describe a satellite orbit by quoting the perigee and apogee height of the SGP4 mean elements relative to a fictitious

6378 km spherical Earth. To find the actual perigee height of a satellite above the true surface of the Earth, one must first apply the SGP4 theory to derive the osculating elements (or, equivalently, state vector) at perigee. For an orbit with significant eccentricity this perigee may be different from the SGP4 mean value by of order 10 km. Next, the correction to the height above the Earth ellipsoid rather than the spherical Earth model ranges up to 22 km at the poles. I use the WGS-84 ellipsoid for calculations in this paper.

Low perigee TLEs are common for the final element set for a satellite, but in some cases this may represent only the final orbit where perigee is not survived. Single element sets are suspect; for example Kosmos-168 was tracked in a 52×386 km orbit on 1967 Jul 4, but data for surrounding epochs make it clear that this was an erroneous solution with the right period but wrong eccentricity. In particular, for elliptical orbit satellites, as the orbital period decreases and perigee drops below of order 100 km the sequence of mean element solutions show increasing set-to-set noise and an increasing fraction of spurious fits. In a review of an archive of 90 million TLE sets for 43000 satellites I identified 50 satellites where the data are not severely affected by these problems and where geodetic perigee heights of less than 100 km were maintained over 2 or more complete revolutions of the Earth.

A few illustrative examples are shown in Fig. 1. These include the Soviet Elektron-4 satellite (SSN 748) which appears to have made 10 revolutions with perigee at or below 85 km at the time of its reentry in 1997, and the US Centaur AV-031 rocket (SSN 38255) which had perigee geodetic height below 110 km for 4 days prior to reentry, and between 80 and 95 km for much of that time.

To summarize, the lowest possible sustained circular orbits are at of order 125 km altitude, but elliptical orbits with perigees at 100 km can survive for long periods. In contrast, Earth satellites with perigees below 80 km are highly unlikely to complete their next orbit. It is noteworthy that meteors (travelling much more quickly) usually disintegrate in the 70–100 km altitude range, adding to the evidence that this is the region where the atmosphere becomes important.

4.4. Air-space vehicles

Goedhart [2] correctly notes that during ascent a space vehicle reaches 100 km altitudes in quite a short downrange distance, so that usually crossing someone else's territory while in the atmosphere is not an issue, and normal spacecraft landings are similar in this respect, but on reentry a winged spaceplane can be at 60 km altitudes or lower while traversing long ground distances. The issue of airspace violations during spaceplane reentry is therefore something to worry about. Goedhart correctly says that the limit of 'aviation' and aerodynamic rather than ballistic phenomena is at 50 km (and infers that the Paris and Chicago conventions apply up to this limit). He immediately contradicts himself by stating that 'aeroplanes are already capable of flying above the 50 km limit', which I suspect is a confusion between a true aeroplane and rocketplanes like the X-15. Several authors exhibit this confusion: like the later Shuttle, the X-15 functions as an airplane (in fact, a glider) during descent through the lower atmosphere, and so it looks like an airplane. But when it is above the lower atmosphere it uses rocket thrusters to maneuver - it is then operating as a spacecraft despite its exterior appearance, and makes no use of its aerodynamic surfaces. To use it as an example of a high altitude aircraft is to miss the point.

4.5. Other technological considerations

Goedhart [2] also discusses what he calls the 'biological theory', that at about 20 km humans cannot survive unprotected due to low air pressure, but notes that clearly air vehicles above this line are not considered to be in space.

de Oliveira Bittencourt Neto [6] discusses the idea of 'effective control' (you own the airspace you can control) and points out that's a

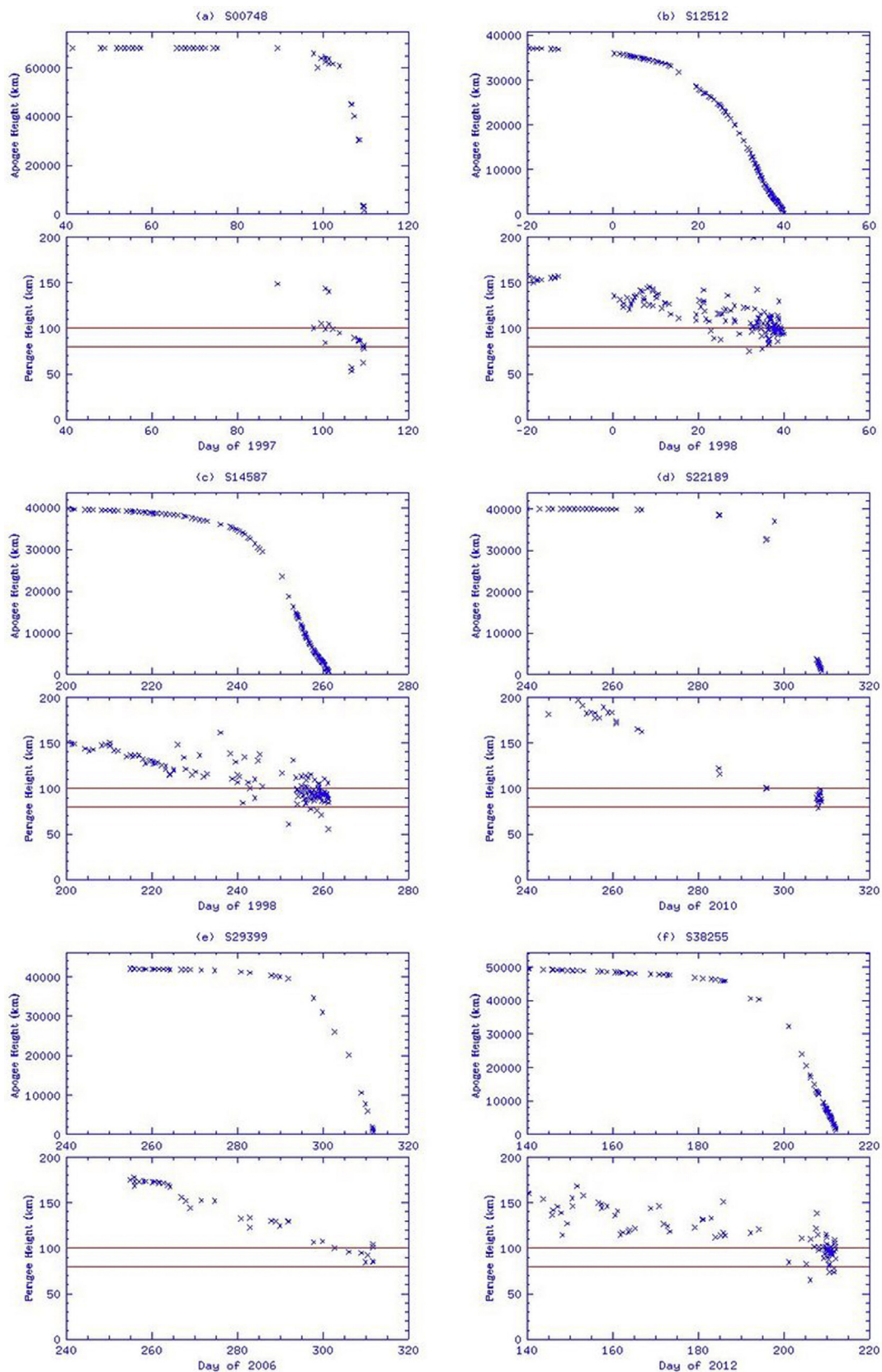


Fig. 1. Geodetic height of apogee and perigee versus time for the decay of selected elliptical orbit satellites. Horizontal lines at 80 and 100 km are superimposed on the perigee plots. Despite noisy fits, these satellites appear to have survived multiple perigee passages below 100 km. (a) Satellite 748 (1964-006 B, Elektron 2, 2D No. 2); (b) Satellite 12512 (1981-30 A, Molniya-3 No. 30); (c) Satellite 14587 (1983-126 A, Kosmos-1518, Oko 6022); (d) Satellite 22189 (1992-069 A, Kosmos-2217, Oko 6059); (e) Satellite 29399 (2006-038 B, Chang Zheng 3 A Y10 third stage rocket); (f) Satellite 38255 (2012-019 B, Centaur AV-031 rocket).

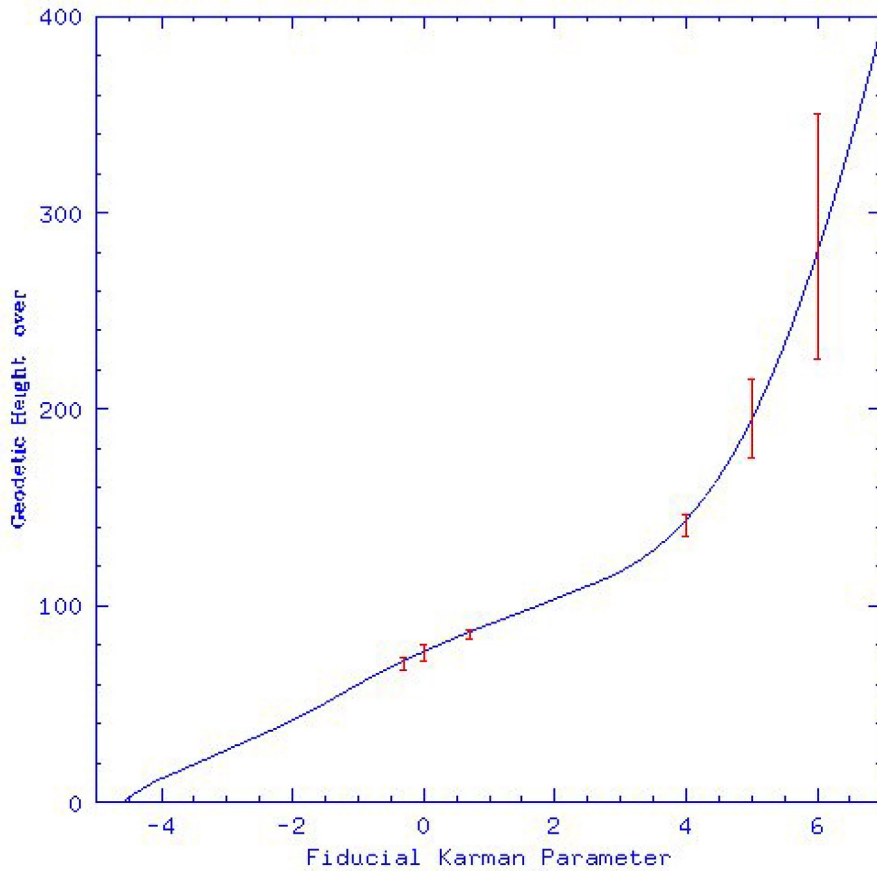


Fig. 2. Fiducial Karman parameter k_0 versus geodetic altitude for US Standard Atmosphere 1976. The vertical error bars summarize the results of Fig. 3 and 4, indicating the range of variation in the altitude for a given value of k_0 found in runs of the NRL atmosphere model for different dates, latitudes and longitudes.

really bad idea as it leads to different boundaries of space above different countries. Satellites would cross such boundaries every few minutes.

It is clear that for a definition of space to be useful and consistent with the generally understood meaning of the term, it should be well above typical airplane altitudes and should be globally uniform (this last constraint does not mean that one can't adopt different globally-uniform definitions of space for different purposes and situations).

5. The effective Karman Line

5.1. Mathematical analysis of the Karman line

The 'von Karman line' appears to be what mathematicians refer to as a 'folk theorem', arising out of a conference discussion but never formally published by him. It was fleshed out in later publications, especially in the influential work of Haley (1963 [3]) and there is some justification for calling it the 'von Karman-Haley line'.

von Karman's argument was that the space boundary should be defined where forces due to orbital dynamics exceed aerodynamic forces. A rough order of magnitude argument was used to show that this was at of order 100 km (as opposed to 10 km or 1000 km), but in reality the von Karman criterion defines a line whose altitude varies with position and time (because of variations in atmospheric density due to solar activity) and with the lift coefficient of the spacecraft.

Haley ([3], p 78) extended the argument to satellite drag and places the line at 84 km. The strong association of the term '(von) Karman line' with a definite 100 km value is a more recent development. In a recent review Gangale [44] untangles this complicated history in detail.

Satellite launch vehicles reach 100 km altitude in the first minutes

of flight, well before they have accelerated to orbital velocity; thus the appropriate value of the parameter f is less than one, and drag is smaller and the gravity/drag force ratio correspondingly larger at a given altitude; hence the effective Karman line is even lower in this phase or for suborbital missions. I will consider only orbital flight in the following calculations.

I consider a spacecraft of mass m , cross sectional area A and lift and drag coefficients C_L and C_D travelling at velocity v , which I'll later take to be the orbital Keplerian circular velocity v_c . The spacecraft is travelling at geocentric radius r through atmosphere of density ρ in the gravity field of the Earth whose mass is M_E .

The lift force is

$$F = \frac{1}{2}AC_L\rho v^2 \tag{1}$$

and the drag force is expressed by the same equation with a different coefficient C_D .

Following Haley I consider that drag forces are more relevant to Earth satellites, so instead consider the ratio of drag force to weight (i.e. to gravitational pull). Because atmospheric density changes by many orders of magnitude in a few tens of kilometers, use of C_D rather than C_L does not change the final Karman Line location much, as we shall see below.

The ratio of gravitational force (weight W) to aerodynamic force (F) is

$$R = W/F = \frac{mg}{\frac{1}{2}AC_D\rho v^2} \tag{2}$$

where the local acceleration due to gravity is

$$g = GM_E/r^2 \tag{3}$$

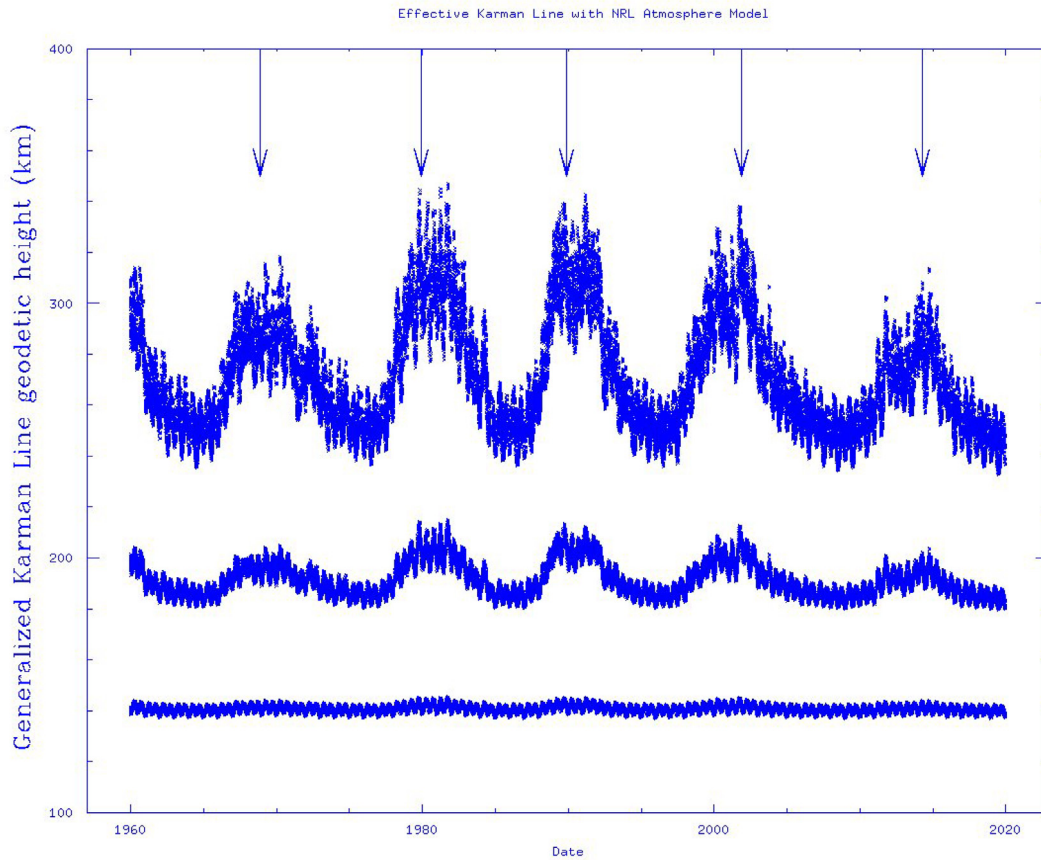


Fig. 3. Curves showing z (4) (lowest), z (5) and z (6) (highest) as a function of time, showing that the effects of the solar cycle are more important at high Karman parameter. These integrations are for NRL atmosphere models evaluated at 45 deg N, but curves for other latitudes are similar. Arrows indicate dates of solar maxima.

and circular orbital velocity is

$$v = \sqrt{GM_E/r} \tag{4}$$

We introduce the ballistic coefficient $B = C_D A/m$, which is essentially the specific drag, or drag per unit mass (warning: some authors use the term ballistic coefficient for $1/B$ instead). Then the above results can be simplified to

$$R = \frac{2}{Br\rho} \tag{5}$$

When R is much greater than unity, orbital dynamics dominates aerodynamics (and, per the original von Karman argument, lifting flight is not possible).

Because of the rapid change of density with height, R changes by orders of magnitude in the range of interest. It is therefore convenient to instead use the logarithm - I define

$$k(B, r, \rho) = \log_{10} R = \log_{10} \left(\frac{2}{Br\rho} \right) \tag{6}$$

and call this logarithmic measure the **Karman parameter**.¹

5.2. Reference ballistic coefficient and fiducial Karman parameter

The Karman parameter is a function of position, atmospheric

¹ Reijnen [16] suggests a slightly different parameter, the height at which drag reduces the height of a single circular orbit by 10% (and thus its radius from Earth center by about 0.2%). If δ is the fractional change in the semi-major axis. Reijnen claims $\delta r = 2\pi B\rho r^2$. So $\delta = R$, hence Reijnen's criterion corresponds to a Karman parameter k of -2.7 rather than 0.

properties, and spacecraft ballistic coefficient B . With a known atmospheric profile and value of B , one can derive $z_B(k)$, the altitude at which k has a particular value. The value $k = 0$ defines an effective Karman line height $z_B(0)$ at which aerodynamic and gravitational forces balance.

Let us explore how much that line shifts around for a range of plausible values. Typical values of C_D are 2.0–2.4 for satellites, while typical values of B are of order 0.006–0.05 m²/kg [37], [38]. The International Space Station has an average cross sectional area of 2040 sq m and a B of 0.010 m²/kg, while the Planet Dove cubesats have a cross-sectional area varying from 0.2 to 0.02 sq m and a B of 0.1 to 0.01 depending on flight attitude [39].

However balloons and special high density satellites can have more extreme values. The Echo balloon satellite had a high B of around 22 m²/kg, while the LARES high density geodetic research satellite had a record low B of around 0.001.

As an intermediate fiducial value I adopt $B_0 = 0.01\text{m}^2/\text{kg}$ and define the **fiducial Karman parameter** k_0 as

$$k_0(r, \rho) = k(B_0, r, \rho) \tag{7}$$

so that

$$k(B, r, \rho) = k_0(r, \rho) - \log_{10}(B/B_0) \tag{8}$$

We then define the function $z(x)$ as the geodetic altitude at which $k_0 = x$. The usefulness of k_0 is that its values and the corresponding altitudes $z(k_0)$ can be calculated for a given atmosphere independently of the satellite properties. One may then read off the Karman line location for a particular satellite by determining which value of k_0 is appropriate for its B . For example if one considers a satellite with a high $B = 0.05$, the Karman line $k = 0$ corresponds to $k_0 = \log(5) = 0.70$.

Mathematically,

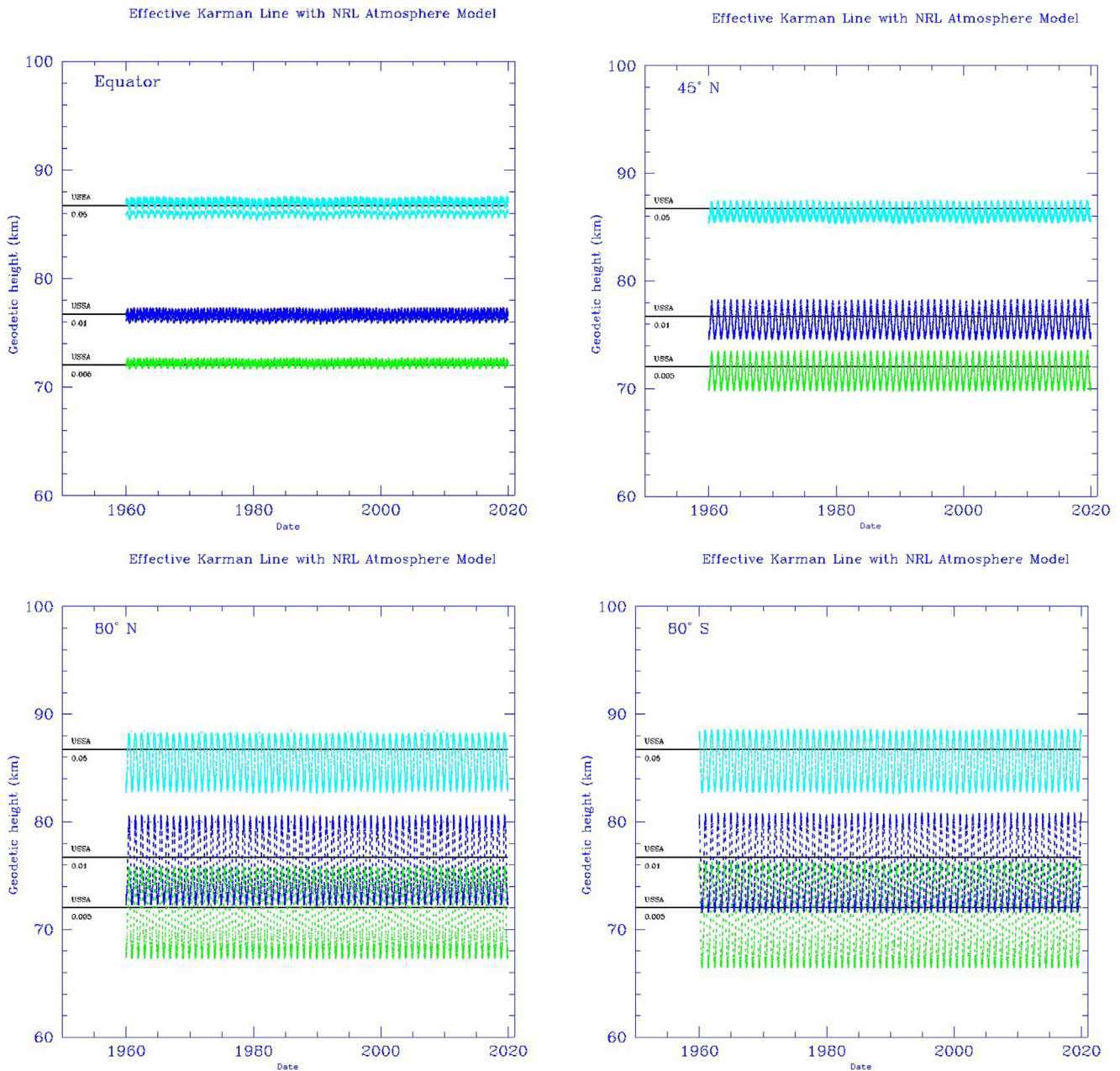


Fig. 4. Curves for $z(-0.3)$, $z(0.0)$, $z(0.7)$, corresponding to the effective Karman line for $B = 0.005, 0.01, 0.05 \text{ m}^2 \text{ kg}^{-1}$ respectively. Each plot gives calculations for a different latitude; there is less atmospheric variation at intermediate latitudes. At these low altitudes the effects of the solar cycle are minimal.

$$z_B(x) = z(x + \log_{10}(B/B_0)) \tag{9}$$

with the Karman line at $x = 0$.

5.3. Numerical evaluation of the effective Karman line

I now derive the geodetic altitude z for various values of the fiducial Karman parameter and consider how the Karman parameter changes with location and time.

A useful reference atmosphere is the US Standard Atmosphere 1976 (hereafter USSA76) [40], which is a single, fixed, atmosphere model. Fig. 2 shows the altitude as a function of fiducial Karman parameter for this atmosphere. However, in practice the atmospheric density at a given altitude varies with longitude and latitude, and also with solar activity as the atmosphere is heated by the solar flux.

To understand the effect of these variations on the function $z(k)$ I ran models for assorted times and geographical locations using a code

which implements the NRL MSISE-00 atmospheric model [41]. Atmospheres were calculated at 10 day intervals from Jan 1960 to Jan 2020 to fully sample several solar cycles. At each selected day atmospheres were calculated for 0, 6, 12 and 18 h GMT at four latitudes (80 S, 0 N, 45 N and 80 N) and four longitudes (0, 90, 180, 270 E). For each epoch, actual or (for future dates) predicted solar activity levels from the Celestrak space weather archive [42] [43], were used.

In Fig. 3 I show the $z(k_0)$ lines for high values of k_0 , namely $k_0 = 4, 5, 6$. There are high amplitude variations in the $k_0 = 6$ Karman line correlated with the solar cycle, reflecting the well-known sensitivity of atmospheric density to solar flux at the corresponding altitudes, above the mesopause. Note, however, the much reduced amplitude of the variations at lower altitudes and Karman parameter values. The USSA76 model values are in all cases within the range of the NRL model variations; the range of the variations at each modelled parameter value is summarized as an error bar on the USSA76 curve in Fig. 2.

In particular we are interested in fiducial Karman parameters k_0 equal to $-0.3, 0.0, +0.7$, corresponding to effective Karman lines $k = 0$ covering the typical range of B for satellites discussed above. The USSA1976 reference model gives $z(-0.3) = 72.0$ km, $z(0.0) = 76.7$ km, and $z(0.7) = 86.7$ km. In Fig. 4 I show corresponding NRL model atmosphere calculations as a function of time. Seasonal variations are most prominent at polar latitudes but their amplitude is only a few kilometres. The fact that actual historical solar flux values for each date were used confirm that irregular solar flares do not affect the result.

In all cases the effective Karman lines calculated from the NRL atmospheres remain within 5 km or so of their USSA values, and the overall range of the data (for a factor of 10 in ballistic coefficient) is from 66 to 88 km. In other words, the region where aerodynamic forces transition from dominant to negligible is relatively well defined despite typical variations in satellite and atmosphere properties (at least to the extent that this atmosphere model reflects reality). The range of ballistic coefficients considered here is comparable to the difference between typical lift and drag coefficients, and so this conclusion still holds if the original lift-based Karman criterion is preferred.

It is true that for satellites with extreme properties the results do change - for a balloon satellite like Echo, the effective Karman line $z(1)$ is around 140 km. For a very dense satellite such as LARES, the effective Karman line $z(-1)$ is around 60 km.

It is undesirable to have a definition that will change with improving technology, so one might argue that the correct way to define space is to pick the lowest altitude at which any satellite can remain in orbit, and thus the lowest ballistic coefficient possible should be adopted - a 10-m-diameter solid sphere of pure osmium, perhaps, which would have B of $8 \times 10^{-6} \text{m}^2/\text{kg}$ and an effective Karman line of $z(-4)$ at the tropopause. In practice $z(0)$ seems a more realistic limit for finite orbital lifetime (see previous section). The few high density satellites at low orbital altitudes (e.g. LOADS 2, B of around $0.002 \text{m}^2/\text{kg}$) have reentered when their perigees were around 120 km.

We can summarize the results of this section by saying that for a vehicle of typical ballistic coefficient, $z(0)$ represents the altitude at which gravity will exceed aerodynamic forces for any object in steady flight at that altitude (since such flight must always be at or less than the Keplerian circular velocity for that altitude). That altitude lies in the 70–90 km range, and 100 km is always too high.

5.4. Extension of the Karman argument to elliptical orbits

In section 4.3 I showed that elliptical orbit satellites can survive lower altitudes than circular orbit ones. I now derive the ratio of gravitational to aerodynamic force at the perigee of an elliptical orbit.

For an orbit of eccentricity e , perigee velocity is related to the circular velocity for that altitude by

$$v = v_c \sqrt{1 + e} \quad (10)$$

and so

$$R = \frac{2}{Br\rho(1 + e)}, \quad (11)$$

i.e. the ratio is lowered by a factor of one plus the orbit eccentricity, so the effective Karman line is actually somewhat higher. The low-perigee satellite is indeed drag-dominated near perigee, causing rapid reduction of apogee and consequently reduction of the eccentricity, so that close to reentry the Karman ratio tends to the circular value.

6. Conclusion

I have shown that for a typical satellite ballistic coefficient the effective Karman line is close to (within 10 km of) 80 km independent of solar and atmospheric conditions, rather than the currently popular 100 km value; and that historical orbital data for actual artificial

satellites confirms that orbiting objects can survive multiple perigees at altitudes around 80–90 km. This altitude range is consistent with the highest physical boundary of the atmosphere, i.e. the mesopause, and with the 50-mile ‘astronaut wings’ boundary suggested by the United States during the first years of the Space Age.

On the basis of these physical, technological and historical arguments, I therefore suggest that a value of 80 km is a more suitable choice to use as the canonical lower ‘edge of space’ in circumstances where such a dividing line between atmosphere and space is desired.

Declarations of interest

None.

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