Where Space Begins: Revisiting the Karman Line

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Some questions one might ask:

- Where should the legal boundary of space be?
- Should there be a defined legal boundary at all?

Some questions one might ask -
but I can't help you with:

- Where should the legal boundary of space be?

- Should there be a defined legal boundary at all?

IANAL

Instead I will ask from a scientific point of view:
IF you want to set a boundary of space,
THEN where should it be?

Where does space start?

Why do I care?

Who is an astronaut and who is not?
- Nick Hague reached 93 km in October; did he fly in space?

Which objects are in space and which are not?
When was the first rocket launched into space by a particular country?
What does it mean to be in outer space?

All these issues are ones that people are interested in, indepedently of any legal implications.

I will argue that there is in fact a fairly well-defined boundary of space
I will argue that it is NOT the 100 km line

- and I believe this technical background should at least constitute relevant input to the legal arguments on the subject.

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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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Historical choices

One of the earliest definitions was around 1960, when the US Air Force declared that pilots who reached 50 statute miles altitude (i.e. ~80 km) would be awarded ‘astronaut wings’

On 17 Jul 1962 Maj. Robert F. White became the first US pilot to do so outside the Mercury program during an X-15 flight to 95 km

7 humans have flown above 80 km but not 100 km: should they be in the list of astronauts?

“First into Space on Wings” - LIFE

Technological boundaries I: how high can you fly?

The highest airplanes

We don't count the X-15 and other rocket planes – they don't use their wings until they are about to land. We're looking at how high you can go using aerodyamic lift

The Soviet MiG-25 fighter was modified to a high altitude test plane, the Ye-266

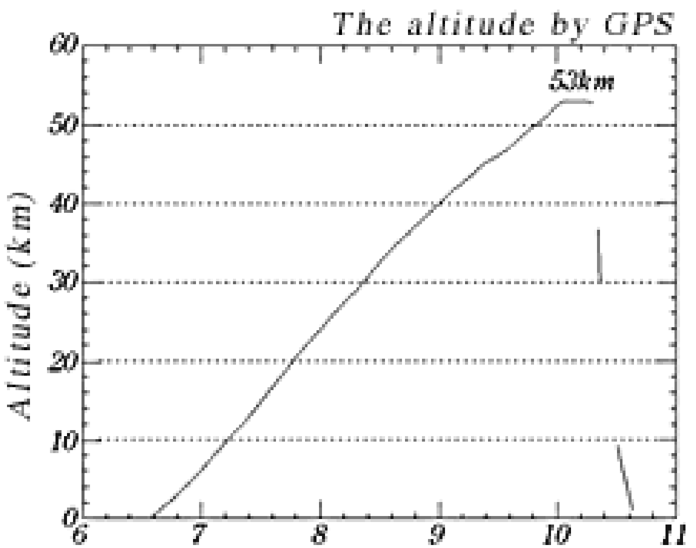
1973 Jul 25: Ye-266 reaches 36.2 km
1977 Aug 31: Alexander Fedotov in Ye-266M reaches 37.7 km (current record)
2001 Aug 14: Helios drone in steady flight at 29 km

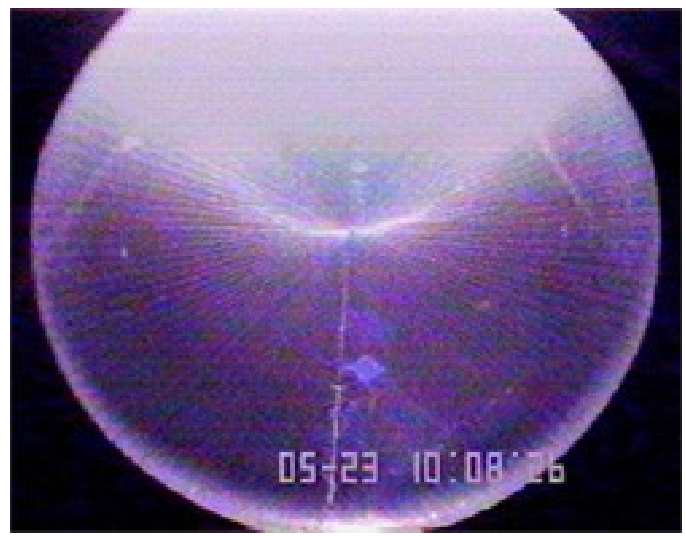
Technological boundaries II: how high can you fly?

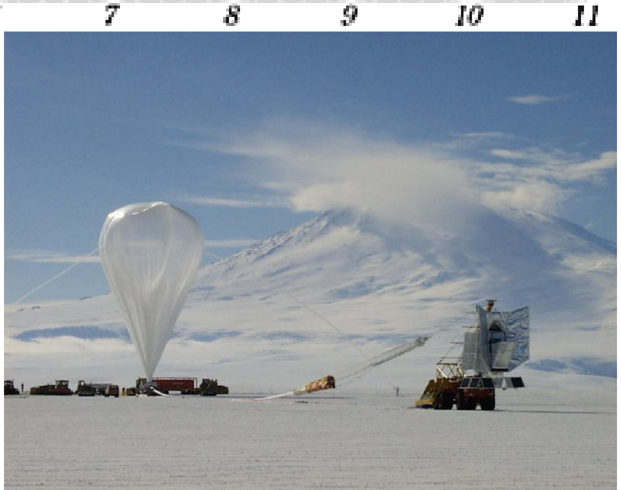
The highest balloons:

1961   crewed balloon reaches 34.6 km (Ross and Prather in Stratolab V)
2014   Alan Eustace in STRATEX reaches 41.5 km

1972   uncrewed balloon reaches 51.8 km (stratopause)
2002 May 23   ISAS BU60-1 balloon reaches 53 km;   diameter is 54 m







Boomerang
42 km

Technological boundaries III: how low a circular orbit can you have?

2016: A new record for low circular orbits

Lixing-1 (China) maneuvers down to 124 x 133 km
Stays there for 3 days before reentry

2016 Aug 15 2040	LEO/S	94.501	485	x	503	x	97.38
2016 Aug 15 2343	LEO/S	94.530	487	x	503	x	97.36
2016 Aug 16 0306	LEO/S	94.530	487	x	503	x	97.37
2016 Aug 16 0440	LEO/S	92.136	217	x	540	x	97.40
2016 Aug 16 1256	LEO/S	87.460	139	x	157	x	97.36
2016 Aug 16 1719	LEO/S	87.133	124	x	140	x	97.36
2016 Aug 17 0355	LEO/S	87.231	128	x	145	x	97.36
2016 Aug 17 1340	LEO/S	87.060	124	x	132	x	97.35
2016 Aug 17 1527	LEO/S	87.060	124	x	133	x	97.36
2016 Aug 17 1940	LEO/S	87.058	124	x	133	x	97.36
2016 Aug 18 0037	LEO/S	87.062	124	x	133	x	97.36
2016 Aug 18 1020	LEO/S	86.857	113	x	123	x	97.35
2016 Aug 19 1227	LEO/S	87.032	122	x	132	x	97.35

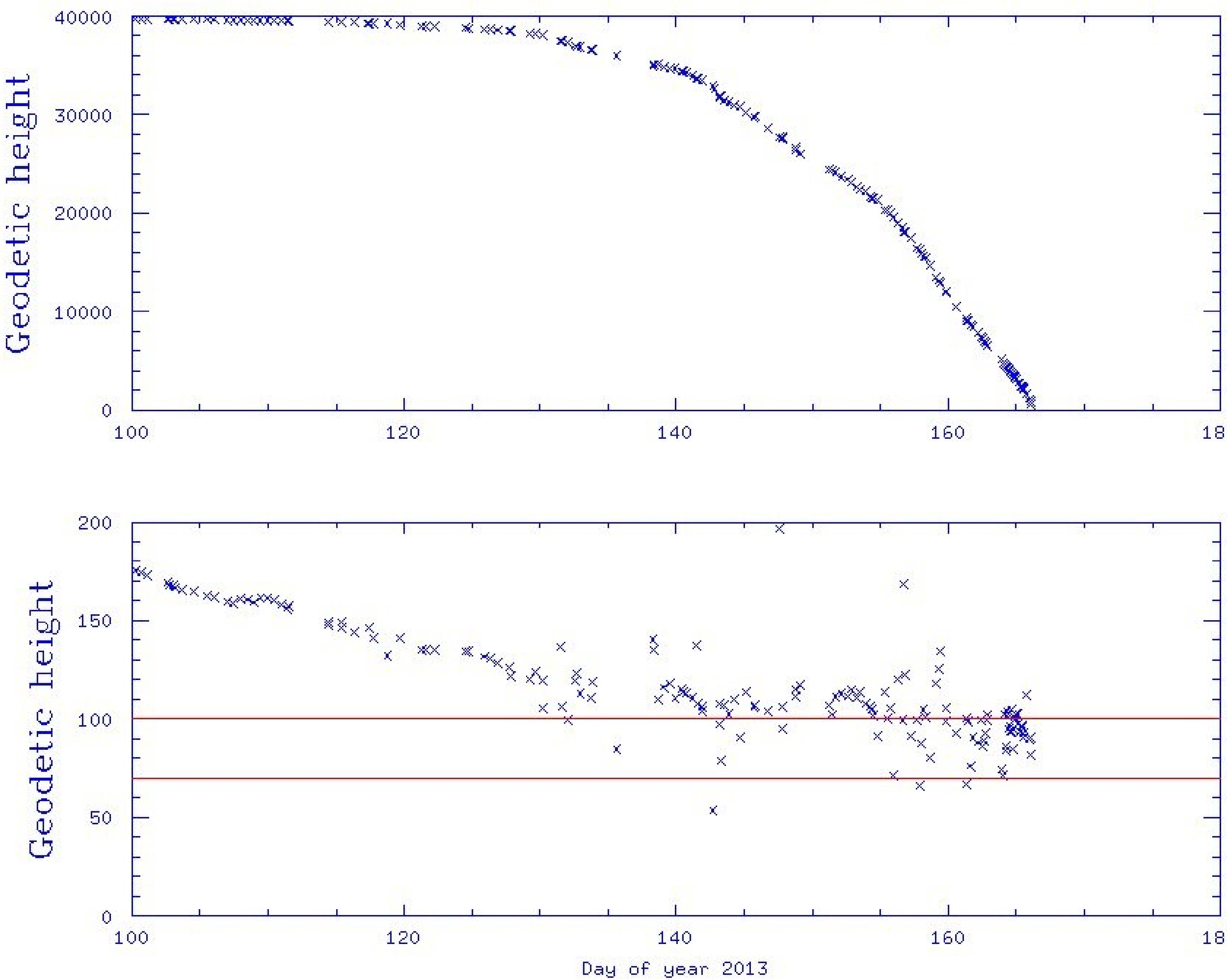
Technological boundaries IV: how low an elliptical orbit can you have?

In highly elliptical orbits satellites can persist for many months with 100-120 km perigees
 - even extended times with
perigees of geodetic height in the 70 to 90 km range!

Satellite 27834 Molniya-3 No. 65

Note to astrodynamicists: TLEs converted to osculating elements at perigee using SGP4
Geocentric perigee converted to geodetic height

Molniya 3-65 (27834) Apogee and Perigee



Assorted elliptical orbit satellites show perigees in the 80-100 km range for days to weeks prior to destructive reentry

These plots show, for 6 satellites, the apogee (upper panels) and perigee (lower panels) vs time

The horizonal pair of lines mark 80 and 100 km.

Apogee and perigee heights converted to geodetic altitudes

Data is noisy, and the TLE fits are sometimes poor, but analysis suggests the result is robust

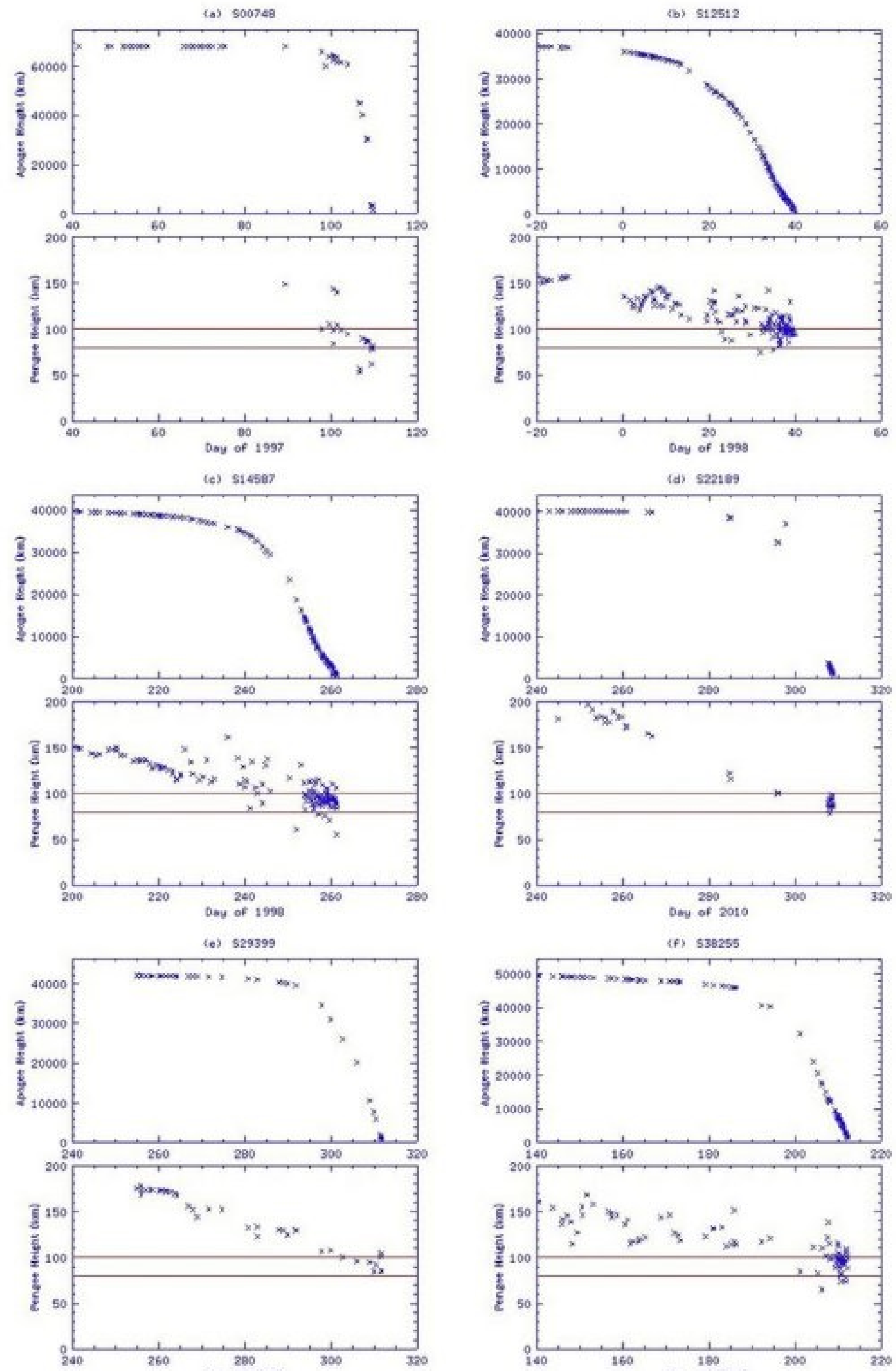


Fig. 1. Geodetic height of apogee and perigee versus time for the decay of selected elliptical orbit satellites. Horizontal lines at 80 and 100 km are superimposed on the perigee plots. Despite noisy fits, these satellites appear to have survived multiple perigee passages below 100 km. (a) Satellite 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).

On the other hand:

Shuttle External Tank

Orbit 74 x 300 km

Result: burns up at first perigee

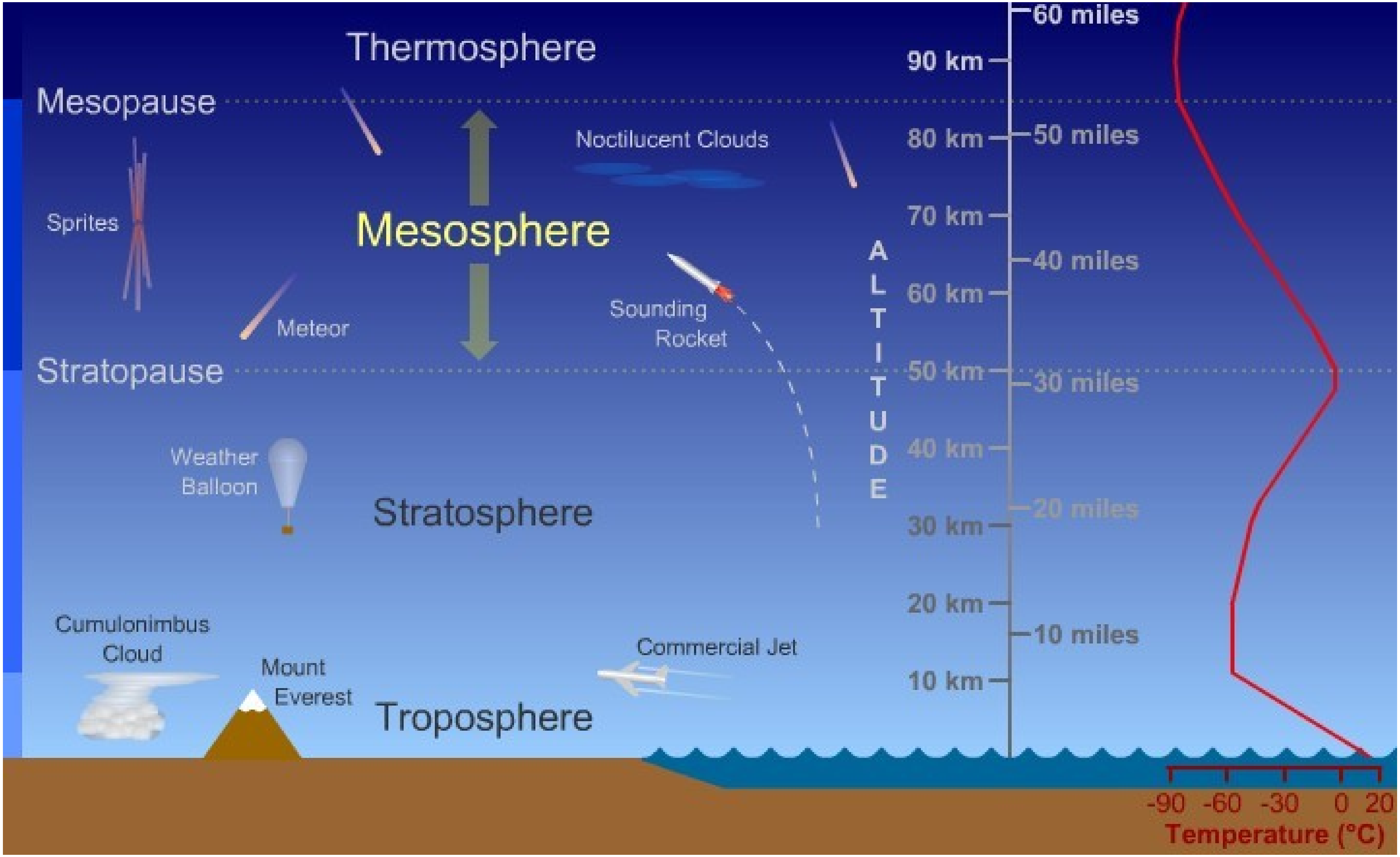
No known satellites survive perigee of less than 70 km

Perigees of 90 km can be surivivable for a while

Space Shuttle main tank re-entry over Hawaii, April, 1985

Image: Dale Cruikshank

Physical boundaries



Credit: R. Russell, UCAR

The Von Karman-Haley line

In the mid 1960s the main rival to the 50 mile rule emerged as the 'von Karman line' - nowadays usually taken to be 100 km

von Karman's argument was that the line should be drawn where orbital dynamics forces exceed aerodynamic forces. His rough order of magnitude estimate was that this would be around 100 km – but this was not originally considered part of the definition

He used it in the context of a lifting spaceplane but others later used the idea for a satellite with drag.

VK discussed this at a conference but appears not to have published it formally at the time (? Anyone have counter evidence?)

Andrew Haley (1963) elaborated the the argument in his book on 'Space Law and Government' and that's what made the idea widespread.

Haley put von Karman's line at 84 km
The 100 km as a standard value is much more recent.

Thomas Gangale – Journal of Space Law:
"The Non Karman Line" (2018)
reviews the history in detail.

Back to the Karman line

Consider the drag force

$$F = \frac{1}{2} B\rho m v^2$$

which at Keplerian velocity is

$$F_d = \frac{1}{2} B\rho GMm/r$$

Compare to the Newtonian gravity force

$$F_g = GMm/r^2$$

Then

$$k = F_g/F_d = \frac{2}{B\rho r}$$

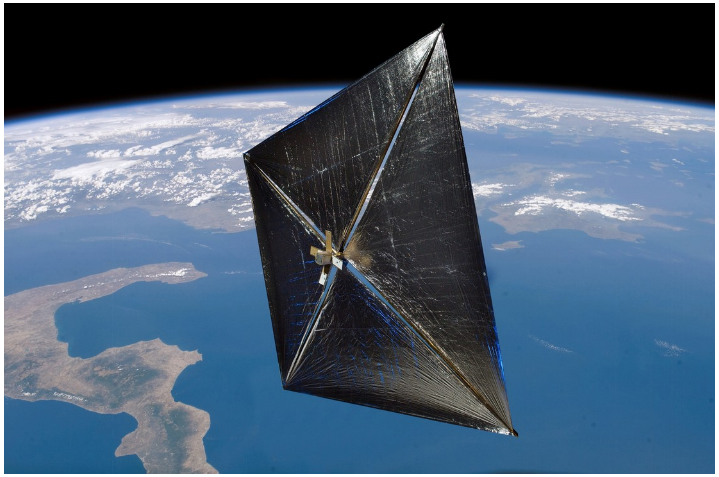
I call k the 'Karman parameter'; if it is more than 1, space effects dominate. It depends on the height, the air density and the ballistic coefficient of the satellite.

For most satellites B is between 0.005 and 0.05 sq m/kg
B = 0.01 sq m/kg is a good typical value

The air density rho depends on
- latitude and (weakly) longitude
- time, both from periodic effects and solar activity

Use NRL MSISE-2000 atmosphere model to evaluate this

Aerodynamic force depends on “Ballistic Coefficient”
- how easily are you blown about in the wind?

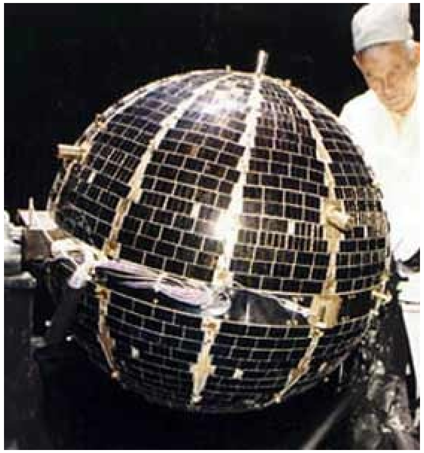


“Sail”

B=0.005 m**2/kg

“Normal”

B=0.01 m**2/kg

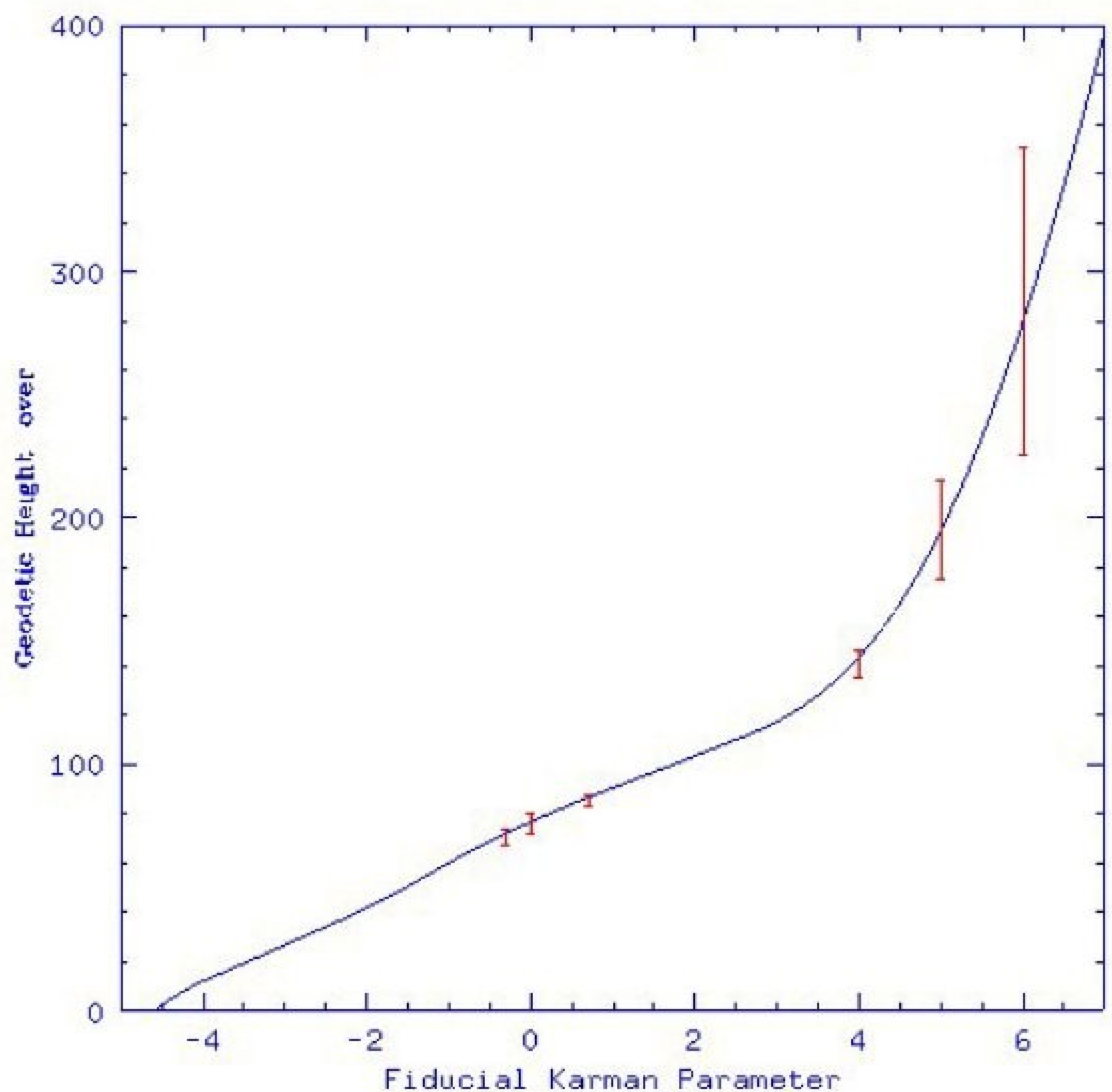


“Cannonball”

B=0.05 m**2/kg

We also need to know how dense the air is versus height above the Earth

Then ask: at what height does ratio (gravity / aerodynamics) equal 0.01, 0.1, 1, 10, 100...



log (gravity / aerodynamics)

USSA 1976
B=0.01 m**2/kg

Atmosphere density at any particular height varies with:

- Latitude
- Time of day
- Time of year
- Solar activity

among other things.

Use the NRL atmosphere model

Calculate where the effective Karman line is:

- for EVERY DAY of the space age
- at 4 different latitudes
- at 4 times of day
- using the archive of solar activity levels

Do this for each of 3 satellite types

- Sail, Normal, Cannonball

First, note that we **could** get an answer that is not well defined
Let's look not at a Karman ratio (gravity/aerodyn) of 1,
but instead a ratio of 10000, 100000, 1 million

- where is the line where gravity is 1 million times stronger than aerodynamics?

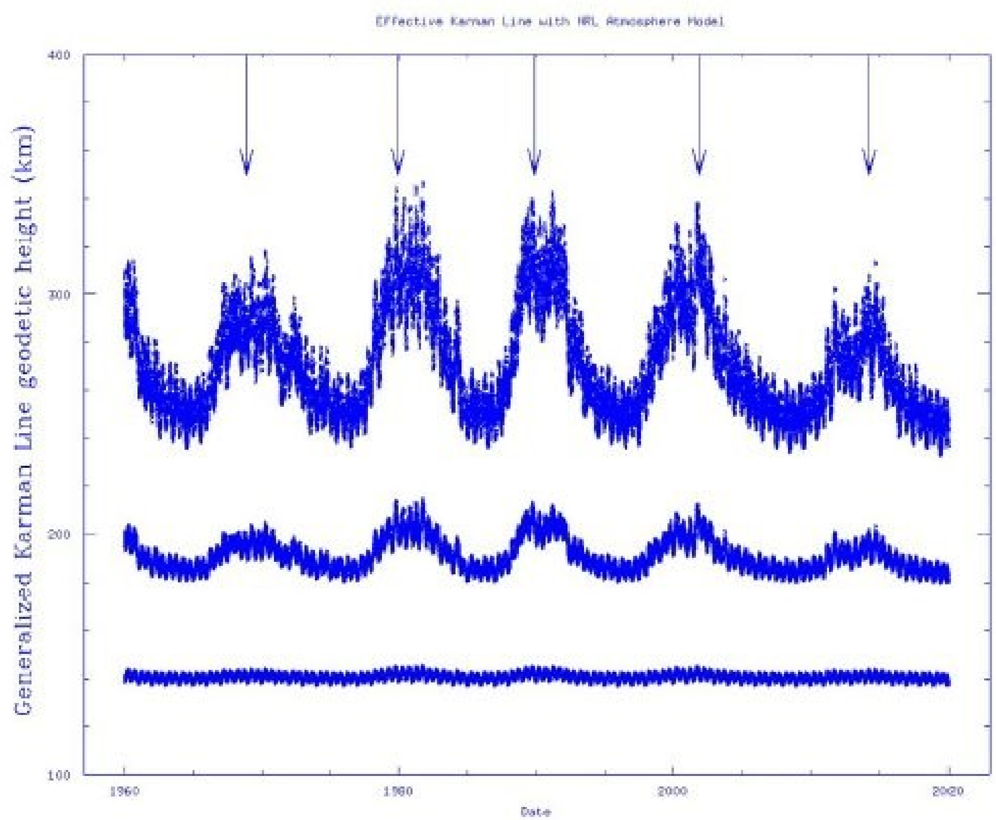
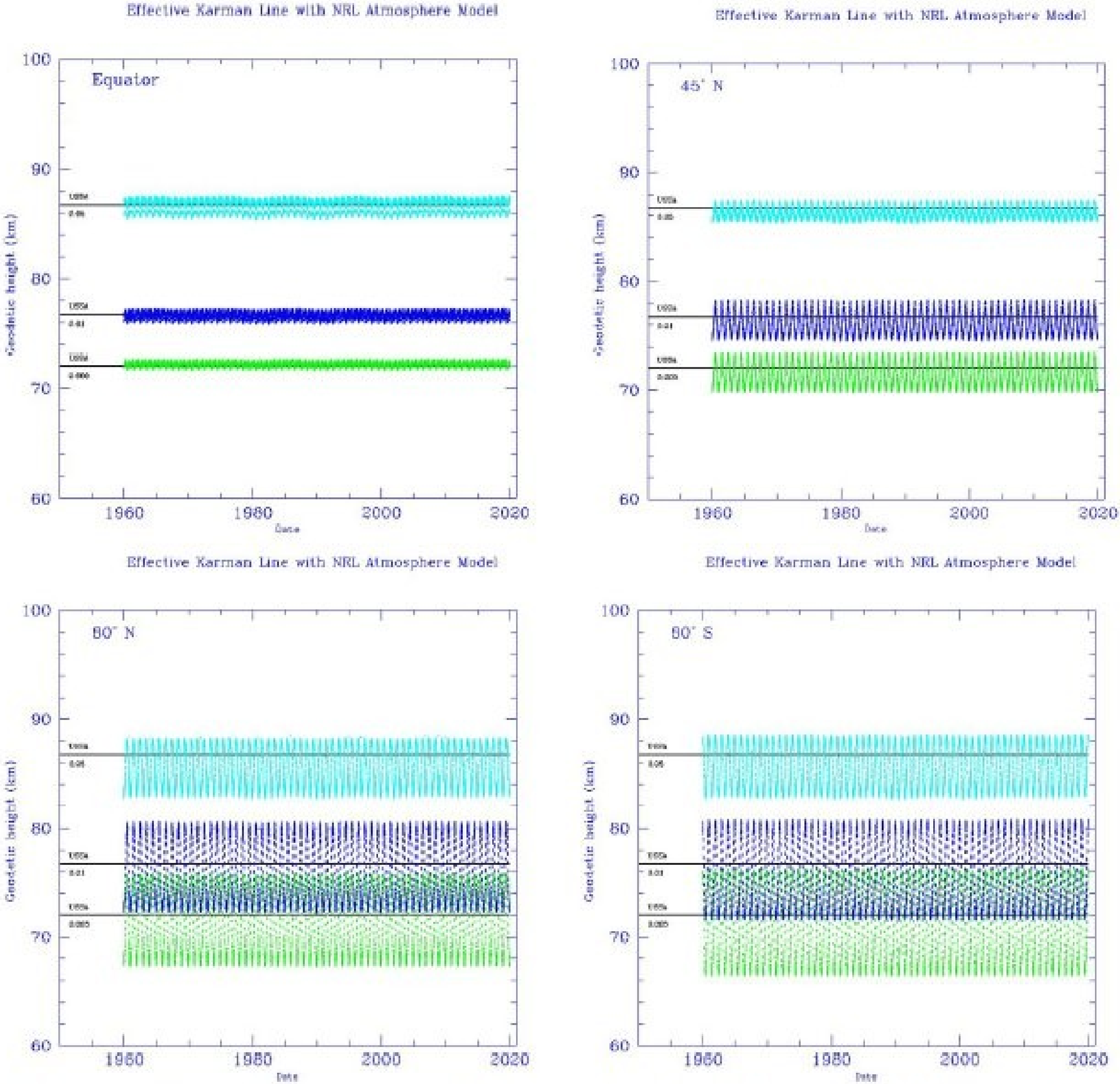


Fig. 3. Curves showing z (4) (lowest), z (5) and z (6) (highest) as a function of time, showing that the effects of the solar cycle are more important at high Karman parameter. These integrations are for NRL atmosphere models evaluated at 45 deg N, but curves for other latitudes are similar. Arrows indicate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

Solar cycle makes the answer vary from 250 to 350 km
- about 30%

But solar activity MUCH LESS IMPORTANT for lower altitudes
For Karman ratio of 1, we're down near 80 km, matters hardly at all



Atmosphere changes with latitude

Also with time of year and solar X-ray flux

Cyan, Blue, Green = 3 different ballistic coefficients (“sail”, “normal”, “cannonball”)

Result always in 65-90 km region

Fig. 4. Curves for z (−0.3), z (0.0), z (0.7), corresponding to the effective Karman line for $B = 0.005, 0.01, 0.05 m^2 kg^{-1}$ 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.

CONCLUSION

1) Elliptical orbit satellites can sustain perigees of 80-90 km but not 70 km

2) Lifting vehicles (airplanes, balloons) can operate up to 50 km or so but not 55 km

3) The effective Karman line (gravity force = aerodynamic force) is between 65 and 90 km depending on time, latitude and satellite properties, and is about 77 km for the ‘most typical’ values

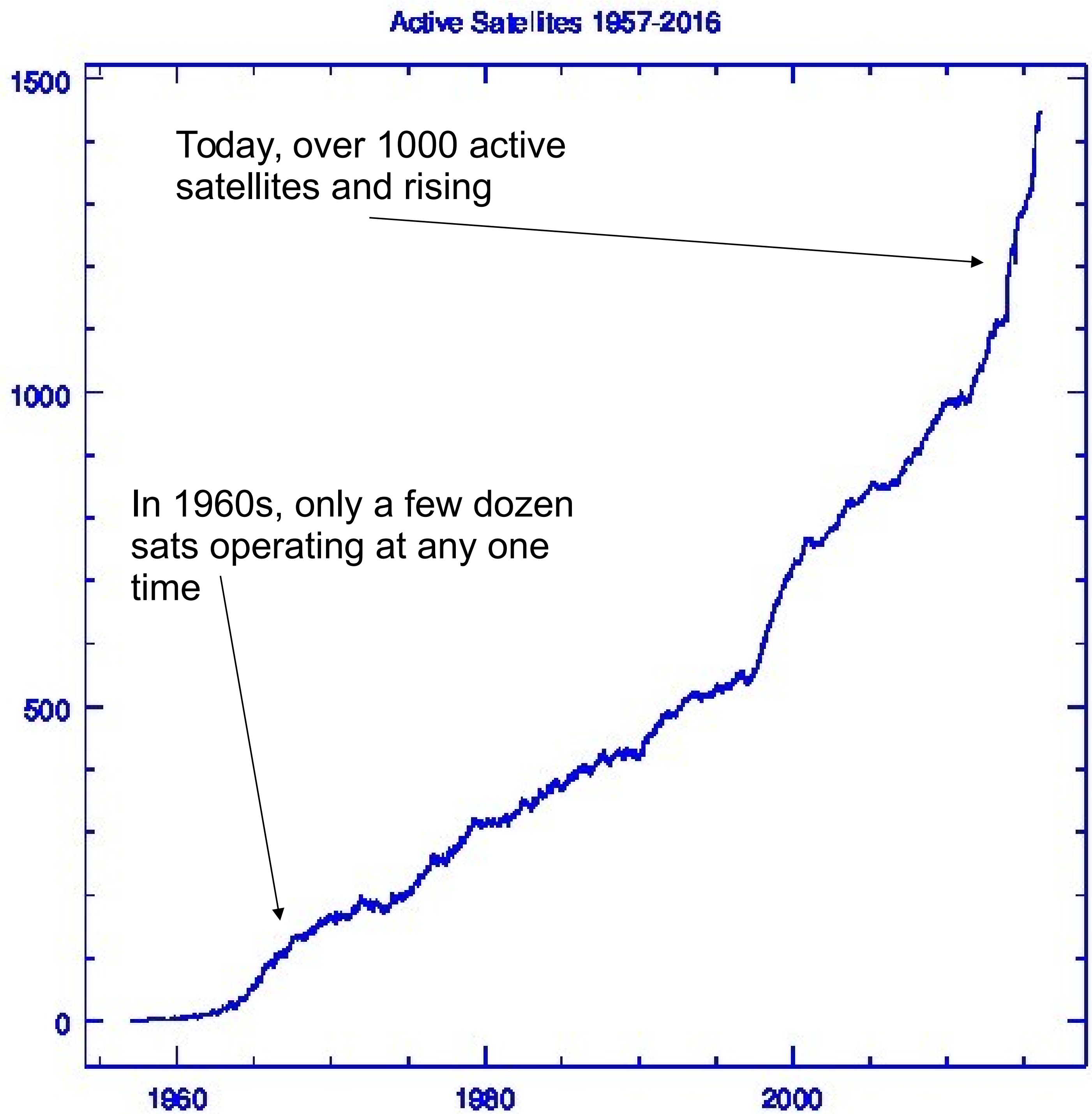
4) The natural physical boundary region is the mesosphere from 50 to (85-100) km or so. The stratopause is at about 50 km, the mesopause varies with time and latitude

Reijnen’s “mesospace”, Sgobba’s “near space”, Pelton’s “protozone” should therefore be located in the physical mesosphere

The USAF were right! 80 km (50 miles) is a good dividing line,
perhaps with a transitional protozone or ‘mesozone’ underneath it extending from 50 or 65 km to 80 or 90 km.

I propose that – for *scientific* purposes:

Geodetic heights up to 50 km are ‘air’
Geodetic heights above 80 km are ‘space’
Geodetic heights from 50 to 80 km are the ‘protozone’ or ‘mesozone’


Active Satellites 1957-2016
1500
1000
500
0
1960
1980
2000
Today, over 1000 active satellites and rising
In 1960s, only a few dozen sats operating at any one time

The Growth of Space Junk