The Edge of Space

or

How Low Can You Go?

Jonathan McDowell

Where does space start?

Why do we care?

I make lists – what rockets reach space, which people have flown in space. What makes the list and what doesn't? So I have to choose.

More importantly, you have to decide where space law applies and where it does not

How do we decide?

Let's look at several criteria:

- historical/cultural
- technological
- physics-based

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

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

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 (? 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.

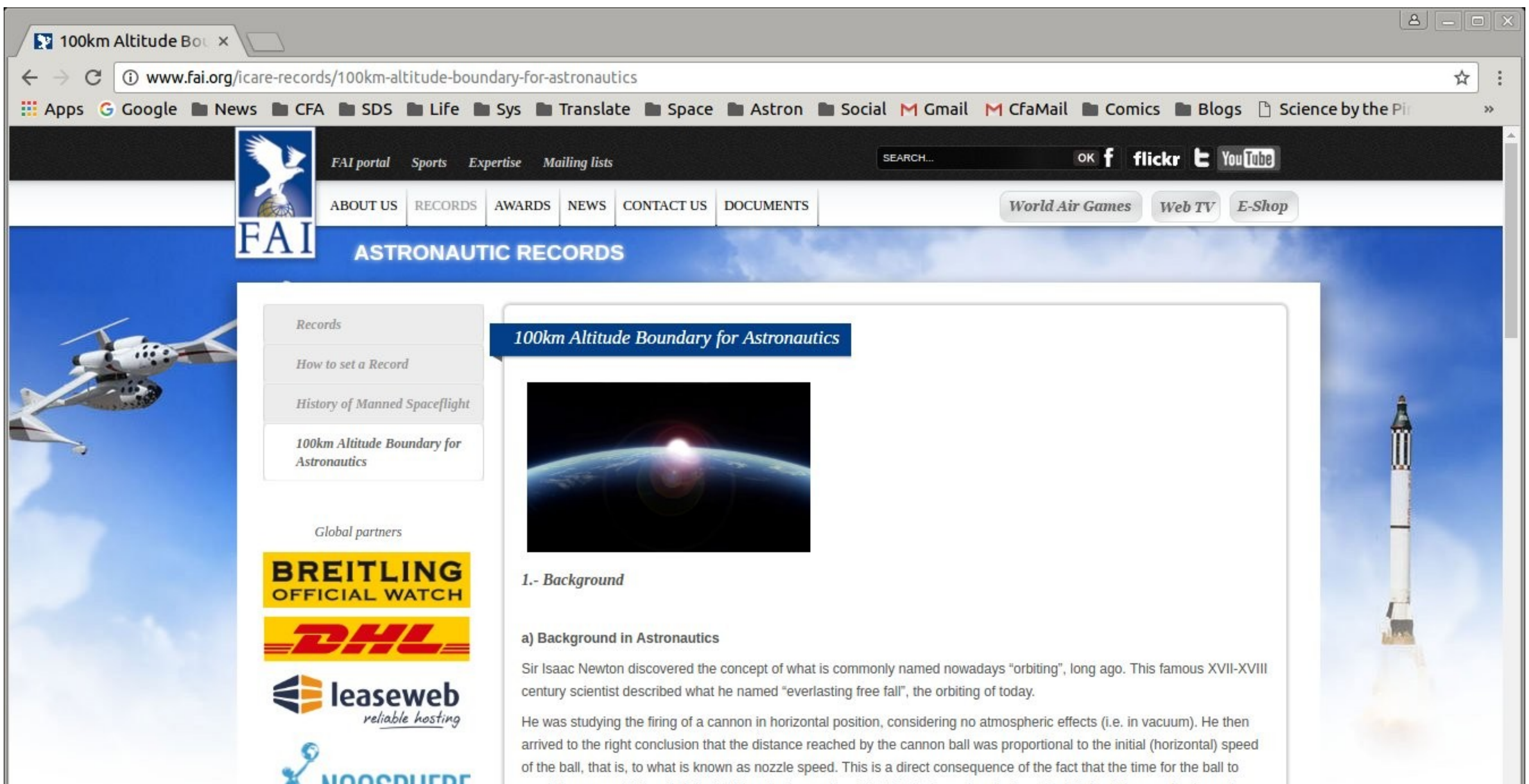
I’ll return to this later...

If you search online you find the FAI web site’s article on a 100 km boundary for astronautics adopted for FAI records

http://www.fai.org/icare-records/100km-altitude-boundary-for-astronautics

Its justification section unfortunately is poorly researched – incomplete information about the X-15, and erroneous information on the lowest satellite orbits.

I conclude that while the FAI can do what it wants, their choice is not a compelling reason to adopt this boundary for other applications



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

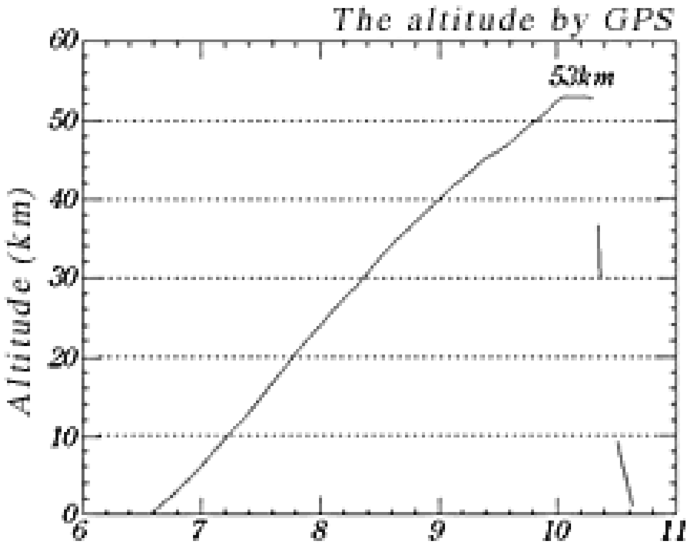
1973 Jul 25:   Ye-266 reaches 36.2 km
1977 Aug 31: Alexander Fedotov in Ye-266M reaches 37.7 km (current record)
2001 Aug 14: Helios drone in steady flight at 29 km

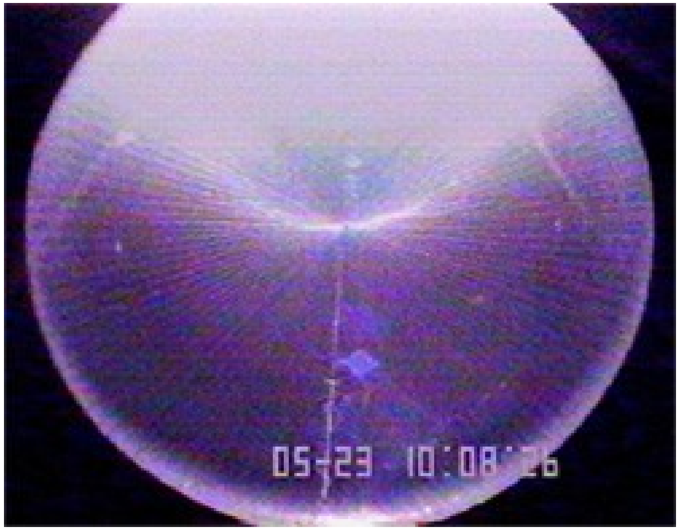
Technological boundaries II: how high can you fly?

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



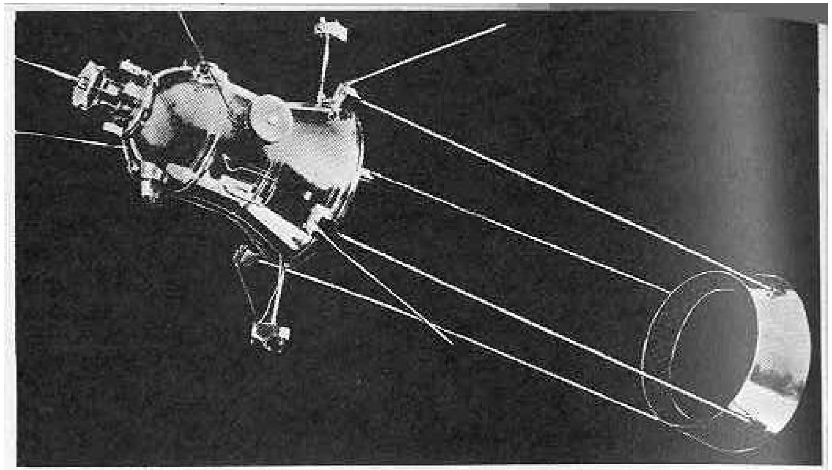


Boomerang
42 km

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

Lowest circular orbits:

Some articles, like the FAI one, talk about the USSR DS-MO No. 1 satellite, codenamed Kosmos-149, the first to use aerodynamic stablizer for attitude control at low orbital altitudes. Its orbit was 245 x 285 km – some have gone much lower

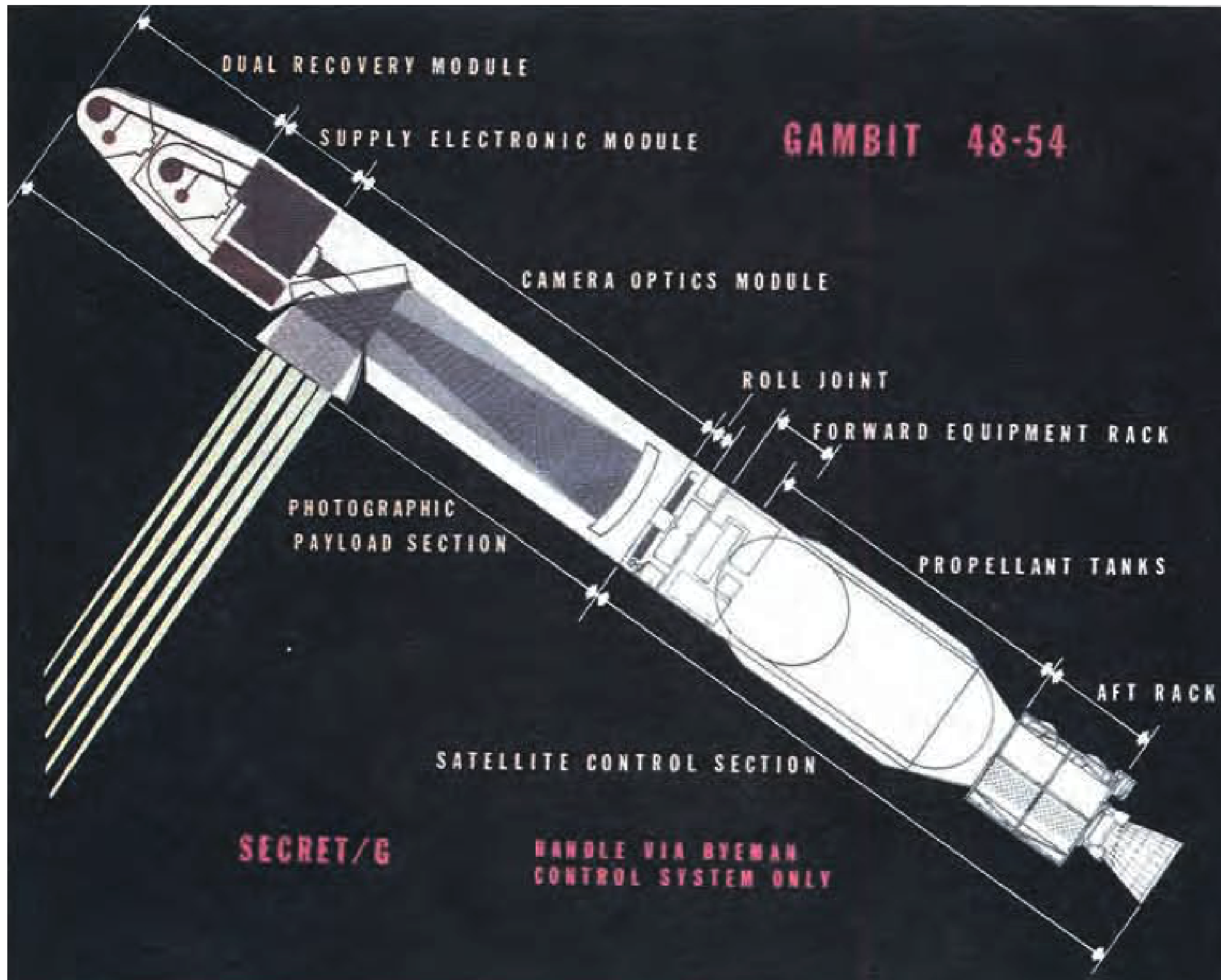


Cosmos 149, Earth-oriented meteorological satellite, was in orbit 17 days

1976 March to May: GAMBIT Mission 4346 (US NRO)

125 x 345 km orbit maintained for 2 months

Similar orbits used for 7 more missions from 1977-1984



1985: Proton rocket stage left in 190 km circular orbit

Takes 2.5 days to reenter

Last tracked orbit 136 x 139 km

This is pretty typical of stages left in low orbit
 - not an unusual or exceptional case

1985	Nov	15	1546	LEO/I	88.324	186	x	196	x	51.64	281.1
1985	Nov	15	1714	LEO/I	88.316	186	x	196	x	51.64	280.8
1985	Nov	15	2139	LEO/I	88.283	185	x	194	x	51.64	279.8
1985	Nov	16	0756	LEO/I	88.188	180	x	189	x	51.64	277.4
1985	Nov	16	1052	LEO/I	88.161	179	x	187	x	51.64	276.7
1985	Nov	16	1812	LEO/I	88.088	176	x	182	x	51.63	275.0
1985	Nov	17	0132	LEO/I	87.997	172	x	177	x	51.63	273.3
1985	Nov	17	0556	LEO/I	87.920	167	x	175	x	51.63	272.2
1985	Nov	17	0724	LEO/I	87.897	166	x	174	x	51.63	271.9
1985	Nov	17	0724	LEO/I	87.897	166	x	174	x	51.63	271.9
1985	Nov	17	2033	LEO/I	87.601	151	x	159	x	51.63	268.8
1985	Nov	17	2201	LEO/I	87.554	148	x	157	x	51.63	268.5
1985	Nov	18	0350	LEO/I	87.242	136	x	139	x	51.63	267.1

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

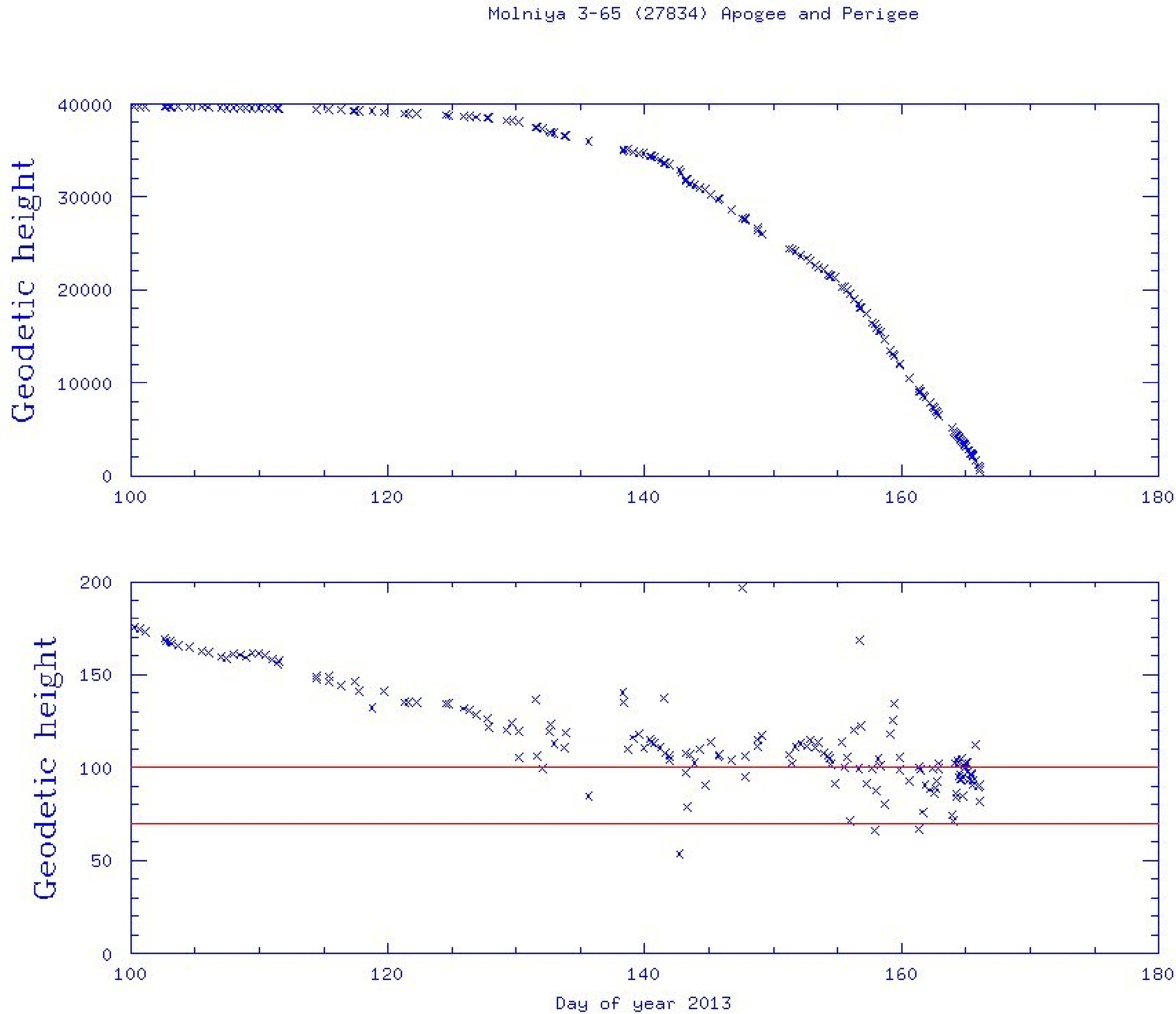
2016	Aug	15	2040	LEO/S	94.501	485	x	503	x	97.38
2016	Aug	15	2343	LEO/S	94.530	487	x	503	x	97.36
2016	Aug	16	0306	LEO/S	94.530	487	x	503	x	97.37
2016	Aug	16	0440	LEO/S	92.136	217	x	540	x	97.40
2016	Aug	16	1256	LEO/S	87.460	139	x	157	x	97.36
2016	Aug	16	1719	LEO/S	87.133	124	x	140	x	97.36
2016	Aug	17	0355	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
Geodetic height
40000
30000
20000
10000
0
100
120
140
160
180
Geodetic height
200
150
100
50
0
100
120
140
160
180
Day of year 2013

On the other hand:

Shuttle External Tank

Orbit 74 x 300 km

Result: burns up at first perigee

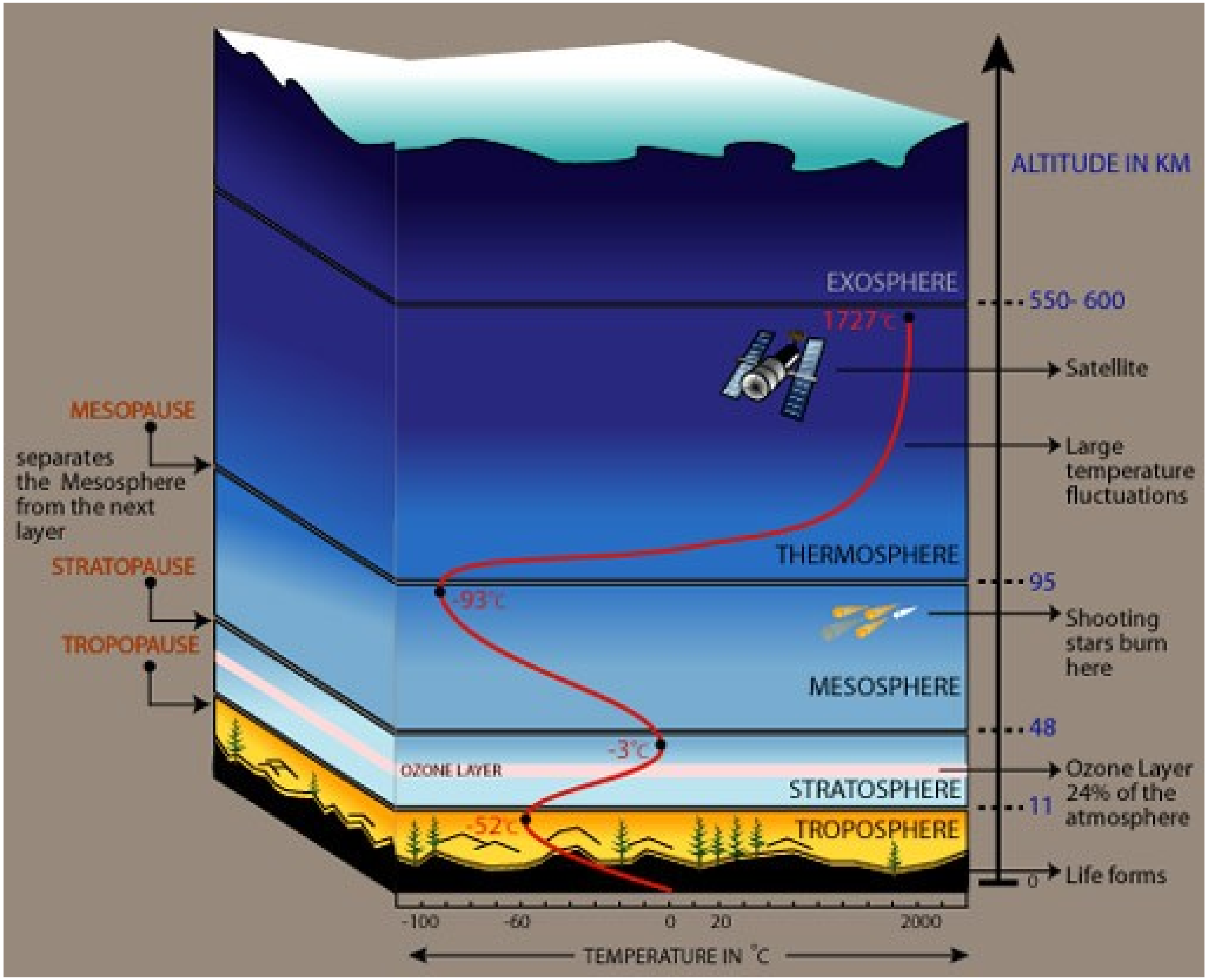
No known satellites survive perigee of less than 70 km

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



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

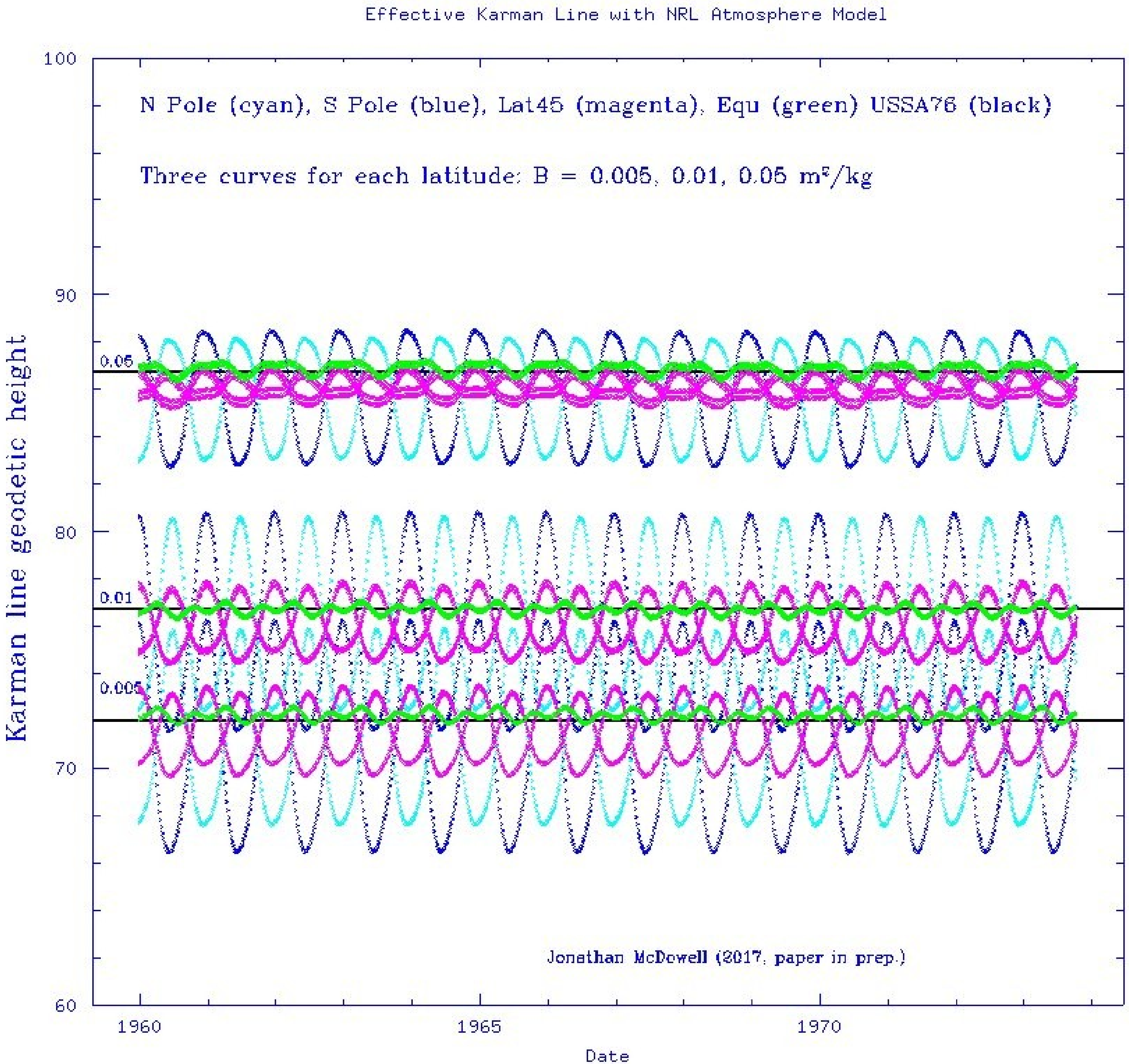
$$k = F_g/F_d = \frac{2}{B\rho r}$$

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


Effective Karman Line with NRL Atmosphere Model
N Pole (cyan), S Pole (blue), Lat45 (magenta), Equ (green) USSA76 (black)
Three curves for each latitude: B = 0.005, 0.01, 0.05 m²/kg
0.05
0.01
0.005
Jonathan McDowell (2017, paper in prep.)
Karman line geodetic height
100
90
80
70
60
1960
1965
1970
Date

CONCLUSION

Satellites can exist down to 90 km or so but not at 70 km, so the bottom edge of ‘space’ should perhaps be in this range

Lifting vehicles (airplanes, balloons) can operate up to 50 km or so, perhaps even 55 km

The effective Karman line is between 65 and 90 km depending on time, latitude and satellite properties

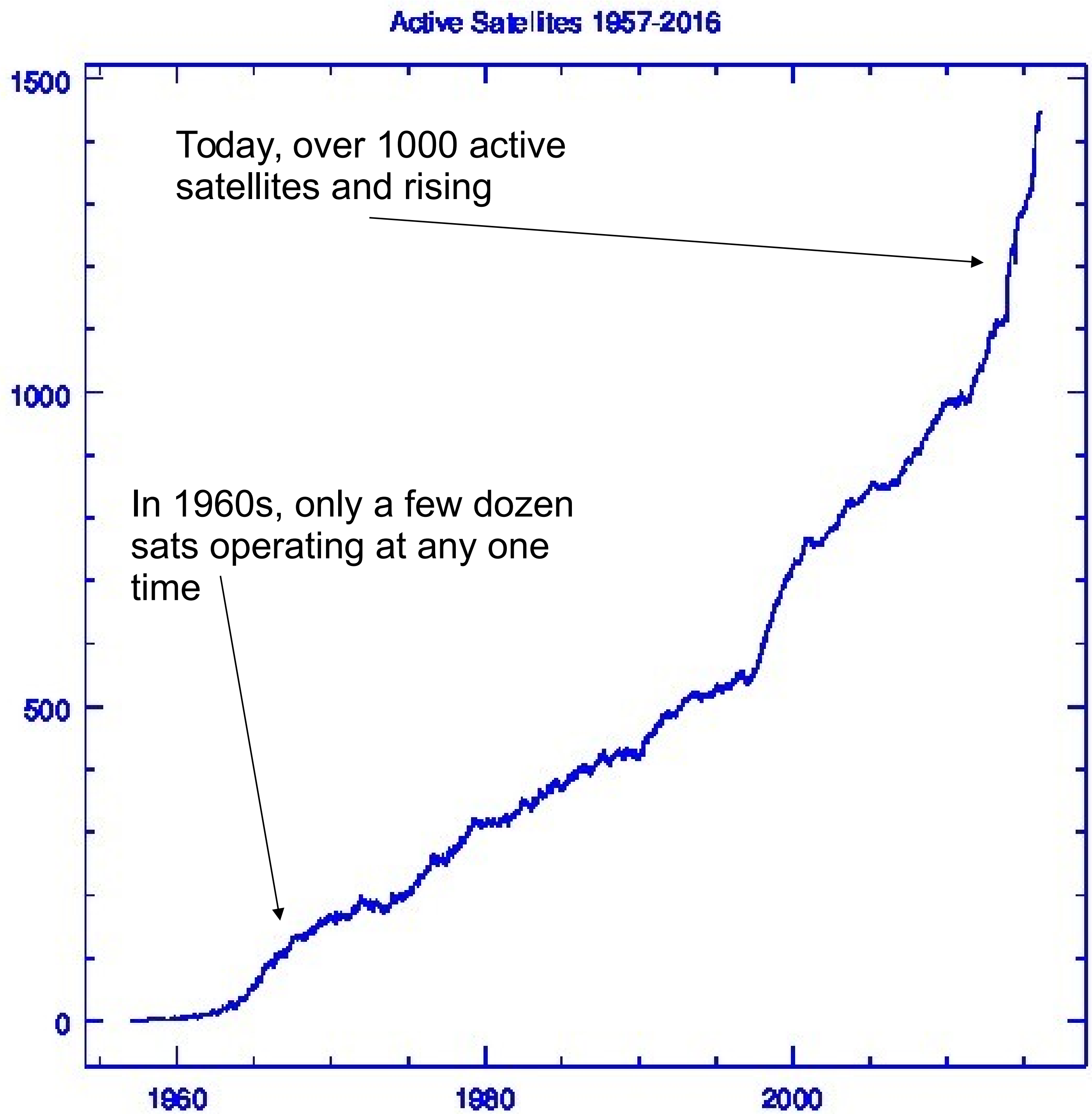
The natural physical boundary region is the mesosphere from 50 to 110 km or so. The stratopause is at about 50 km.

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

The USAF were right: 80 km is a good dividing line,
perhaps with a transitional protozone or ‘mesozone’ extending from 50 or 65 km to 80 or 90 km.

I propose that:

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