**Chapter 1 Sixty Years of satellites**

**1.1 Beginning with the beach ball**

On October 4th 1957, the 40th anniversary of the Bolshevik revolution, the USSR launched Sputnik 1, the first artificial satellite in space. The size of a beach ball and weighing 83.6 kg, Sputnik had transmitters at 20.005 MHz (15 metre wavelength) and 40.002 MHz (7.5 metre wavelength).

Sixty years on, Mr Elon Musk, founder of Space X and the Tesla Motor Company assures us that we will be soon be living on Mars,[[1]](#footnote-1) and flying anywhere on earth in under an hour,[[2]](#footnote-2) Jeff Bezos of Amazon[[3]](#footnote-3) and Richard Branson of Virgin Atlantic [[4]](#footnote-4) have plans for us to holiday in space and Mark Zuckerberg of Facebook aims to connect the unconnected from space.[[5]](#footnote-5) Not to be outdone, The Alphabet Group, the parent holding company for Google, together with the investment group Fidelity have invested $1 billion dollars in Space X in return for a 10% shareholding.[[6]](#footnote-6)

In parallel, the asteroid mining start up Planetary Resources[[7]](#footnote-7) has teamed up with the Duchy of Luxembourg to define a regulatory and legal framework for the ownership of mined resources from the asteroid belt. Goldman Sachs consider that the falling cost of rockets and the vast quantities of platinum sitting on space rocks makes this a hot investment prospect though possibly better suited to the orphans fund rather than the widows fund.[[8]](#footnote-8)

Can a handful of ‘new space’ entrepreneurs, relatively new companies (15 years ago Google had less than 12 employees) and one of the world’s smallest but richest sovereign countries change an industry? Mr Ford certainly made a big difference to the automotive industry and Mr Marconi, in many ways an Edwardian version of Mr Musk, made some big waves, or more precisely, long waves in the wireless industry.

It could be argued that the Marconi business empire was a product of the fading British Empire, fuelled by a mix of consumer and military spending. This model remains relevant today. Every time Kim Jong-un launches another ever longer range missile over Japan, the US ballistics budget gets bigger. Archimedes would have been surprised but probably pleased.[[9]](#footnote-9) The principle of using a perceived enemy, for North Korea, the USA, as the justification for absolute control based on disproportionate military spending is well established. For Henry Eighth, the threat from France was used to justify military spending which more or less bankrupted Tudor Britain but also helped to consolidate Henry’s hold on absolute power. If Henry and Mr Kim could meet today, they would have a lot in common and Mr Kim would undoubtedly be impressed by Henry’s innovative financial remodelling of the medieval monasteries.

**1.2 The USA, Russia and China**

This takes us back or rather indirectly forward to March 23 1983 and an ‘address to the nation’ speech by President Ronald Reagan which came to be known as his ‘Star Wars’ speech (it coincided with Return of The Jedi, the third of the Star Wars films). The speech set out the rationale for an increase in defence spending on space based missile interception predicated on the threat from Russia, the axis of evil as represented to the American public by the US political and popular press. The impact of this shift in spending is still evident today with Space X being active as a launch vehicle for the Boeing built X37B.[[10]](#footnote-10)

The developing military and commercial importance of space was recognised In April 2016 when Congressman Jim Bridenstein, the Republican representative of Oklahoma's 1st Congressional District, sponsored the US Space Renaissance Act.[[11]](#footnote-11) The Act describes space as the ultimate high ground and argues the case for more intensive use by the military of civilian satellite systems both for imaging and reconnaissance, attack detection and space based interception.

Space is also considered as crucial to future cyber security though China rather than the US has being making most of the recent headlines with its successful distribution of quantum cryptographic keys from the Micius low earth orbit satellite achieving a distance of 1200 kilometres, ten times the distance achieved to date over terrestrial fibre.[[12]](#footnote-12)

**1.3 Space Regulation and Deregulation**

Sixty years ago, Sputnik spurred the formation of NASA. The Cuban missile crisis of 1962 highlighted the strategic importance of space. The 1962 Satellite Communications Act *‘allowed the US Government to supervise fair access for commercial satellites’* and coincided with the launch of Telstar 1, the world’s first communications satellite, followed in 1963 by the first geosynchronous satellite. The Satellite Communications Act created Comsat which in 1964 became Intelsat with a membership of 17 nations. In April 1965, the first Intelsat satellite, Early Bird was launched into geostationary orbit to deliver *‘TV and telephone and telegraph and high speed data*’– the world’s first quad play platform. The Intelsat regulatory model was adopted in other regions. Eutelsat was formed in 1977 to operate the first European satellite (launched in 1983). Arabsat was founded in 1976 by the 21 member states of the Arab league.

Inmarsat (the **In**ternational **Mar**itime **Sat**ellite Organisation) had a different starting point, set up as an International Service Operator in 1976 to oversee safety of life at sea (SOLAS). In 1982 Inmarsat started to provide mobile satellite communication services extending to land mobile in 1989 and aeronautical services in 1990. It was the first of the International Satellite Operators to deregulate (in 1999) as a response to the ITU ‘open skies policy’. They were followed by Intelsat and Eutelsat in 2001.

This was not good timing. The dot com bubble had burst in 2000 and the telecom industry followed two years later. The dot com boom had produced a feverish investment in transatlantic fibre and over supply. All that unlit dark fibre meant that per bit long distance delivery prices reduced to almost zero. In parallel, the satellite operators needed to maintain existing terrestrial and space hardware and put together plausible investment plans for new Ku band, K and Ka band constellations.

The result was that the satellite sector started to run uncomfortably high debt ratios. The debt servicing cost of Intelsat is presently equivalent to buying three satellites a year.

Fortuitously income from TV including income from fully amortized C band satellites and military payloads have helped to save the day. If Intelsat is excluded from a financial analysis of satellite operators, the sector is not currently over geared but it is a tribute to the satellite industry and their patient shareholders that they survived their first 15 years in the private sector and remain in a position to justify new R and D and hardware and software investment.

**1.4 The Beach in Bournemouth**

But to get a real flavour of the potential of ‘new space’, we need to take you to the beach in Bournemouth.

Imagine you are a flat panel phased array antenna sitting in a deckchair staring into space. Depending on your latitude you will have RF visibility to at least 50 satellites and this is before 10,000 NEWLEOS arrive in orbit. The smart phone by your side will have RF visibility to at most six cellular sites. It takes twenty minutes for a LEO to travel into space, significantly faster than a truck drop to a cellular site. Having unfurled its antennas, the LEO is ready to go and depending on how it is configured can stay in space for up to 20 years. Outside the earth’s atmosphere, solar energy density is 1,350 W/m2. At the earth’s surface it is 1,000 W/m2. It is sunnier in space. It doesn’t rain in space. Multi junction solar panel cells are now achieving 40% efficiency. So that’s twenty years of free RF power and no rent to pay. Network densification is also easier (less expensive) in space. (There is more space in space). It is also cold in space (-270.45 Celsius) so there is none of that air conditioning nonsense to worry about.

If I want to do some high frequency trading from my deck chair I can get to the other side of the world significantly faster over an inter satellite switched LEO constellation. Radio waves and light travels faster in free space than in a fibre optic cable. Once a fibre optic cable reaches a certain length (about 10,000 kilometres), the free space speed advantage outweighs the round trip distance (1400 kilometres).

Bournemouth, a popular UK south coast resort, happens to be one of the towns in the UK with the worst 4G coverage.[[13]](#footnote-13) From my Bournemouth Council supplied deck chair I can get to Singapore via a LEO satellite network in 120 milliseconds. That is at least 60 milliseconds faster than fibre. LEOSAT are basing their LEO business model on this time differential. And if I really wanted to speed things up then the transaction server would not be in Singapore but in the constellation (with interesting tax implications, another opportunity for those hot shot Luxembourg lawyers).

By contrast if I used my smart phone, my journey to Singapore will be via the local 4G or 5G network, across a microwave link or fibre, cable or copper backhaul then to Singapore which could be along a number of possible routes then into a Singapore network and finally into the Singapore server.

This highlights two points. I have no visibility to the end to end delay across multiple 4G and 5G mobile broadband and backhaul networks. Additionally I have no control over the latency variability (also known as jitter). Apart from introducing uncertainty into the timing of the trade it also makes authentication harder to manage. Challenge and response algorithms depend on deterministic round trip latency and minimal jitter. In comparison, my end to end journey over the LEO constellation gives me absolute control of the end to end channel.

But I also forgot to mention that my deck chair has wheels and an electric motor. It is the Mother of All Deckchairs. And my LEO based server tells me it is sunnier and less crowded at the other end of the beach. I now have two choices. I can self-navigate myself along the beach using the dead reckoning (enabled by the real time high accuracy clock pulse coming down from my nearest LEO satellite) or I can let the LEO drive me. It is probably easier to let the LEO take charge as it knows where all the other deck chairs are and knows that my battery is about to go flat so can take me to the beach hut recharging point where I can take on some power and the latest software upgrade and buy some suntan lotion, a sun hat and an ice cream. Bournemouth by the way claims to be one of the sunniest towns in Britain[[14]](#footnote-14) but everything is relative.

**1.5 Satellites for autonomous transport systems and the internet of moving objects**

This is a trivial example but probably explains why Mr Musk is keen to launch his own LEO satellite network. It will be extremely hard to deliver a totally safe semi-autonomous or fully autonomous driving or terrestrial travel experience over multiple terrestrial cellular networks. It will be relatively easy to deliver a totally safe semi-autonomous or fully autonomous driving or public transport experience over a LEO network. Mr Musk may also have plans to conquer the mobile deckchair market, another $50 billion dollar opportunity?

But this highlights a more general point. Server bandwidth on its own does not confer added value. The value comes from the control that accrues from the data held on the server and the algorithms used to mine and manage that data. This is of course a blindingly obvious statement but explains why the cloud comes (apparently) for free.

There are many stationary and moving objects that are already monitored and managed from space. Inmarsat supply connectivity and management and monitoring systems to 11,000 aircraft. If my deck chair was on a Royal Caribbean cruise ship it would be connected to the internet via the 03b MEO[[15]](#footnote-15) constellation. The constellation is also helping to ensure the cruise ship doesn’t crash into other cruise ships all heading towards Bournemouth (O3b provides complementary support to the Maritime Automatic Identification System). Caterpillar, John Deere, Komatsu and those other manufacturers of massive machines that dig very large holes and crop the wheat fields of America are shipped with Orbcomm VHF modems for asset tracking and (low bandwidth) telemetry and telecommand.

So all we are describing is an expansion of services that are already well established. Inmarsat started providing mobile satellite service in 1982 and a terrestrial service in 1989. Iridium Globalstar and Orbcomm have been providing mobile connectivity for twenty years but these legacy services are based on two way voice and data transmission rather than cloud connectivity.

**1.6 Satellites and 5G – a natural convergence?**

The combination of more satellites and more bandwidth and more on board processing power and storage bandwidth significantly changes the market positioning of the satellite industry and brings it closer to emerging 5G business models.

OneWeb state that they are confident they can substantially reduce 5G backhaul costs both in dense urban and deep rural areas and provide more cost effective mobile and fixed broadband geographic coverage for rural connectivity.[[16]](#footnote-16) This includes IOT connectivity and developing market connectivity where base station electricity is particularly expensive. In developed markets, the proposition could be particularly persuasive for operators presently over dependent on fibre owned and managed by their competitors.

The premise of this chapter and the eleven chapters that follow is therefore simple.

A range of technical, commercial and regulatory innovations in the satellite industry are changing the delivery economics of space based communication. This is sometimes described in the technical and commercial literature as ‘new space’ or Space 2.0 (a reworking of Web 2.0).

This includes hardware innovation in space and on the ground, manufacturing innovation, launch innovation and constellation innovation, in particular the development of mixed constellation delivery platforms combining the benefits of geostationary (GSO), medium earth orbit (MEO) and low earth orbit (LEO) satellites. Constellation innovation includes techniques that allow the same pass bands to be shared between constellations but also significantly with terrestrial 5G systems.

In the satellite industry, business models are based on a combination of spectral assets that include specific access rights to downlink and uplink spectrum, orbit rights and what are usually called landing rights, the right to provide service into and out of sovereign nations visible from geostationary satellites or overflown by MEO and LEO satellites. An established customer basis is also a prime asset.

In the 5G industry, business models are based on spectral access rights combined with pico, micro and macro cell real estate and fibre and microwave backhaul. Money is borrowed on the basis that these access rights will be available over a known period, for example twenty or twenty five years or in some cases indefinitely provided that service obligations are achieved. As with the satellite industry, customers including IOT device subscriptions are an asset against which money can be borrowed and against which enterprise value is assessed.

For the past thirty years the cellular and satellite industry have worked together on a modest scale. Approximately 1% of cellular network backhaul is carried over geostationary satellites. In some extreme geographic locations, satellites are the only way to connect a base station or are more economic than microwave or fibre or copper.

A new generation of satellite operators, who for the sake of simplicity we will refer to as NEWLEO operators, aim to radically change this relationship.

**1.7 The NEWLEOS**

NEWLEO operators include OneWeb, Space X and LEOSAT. OneWeb and Space X have implementation plans based on launching hundreds and ultimately thousands of satellites into low earth orbit. These high count constellations use several GHZ of uplink and downlink Ku, K and Ka band spectrum and longer term plans to use V and W band spectrum. The combination of this spectral bandwidth combined with super-efficient solar panel arrays delivers sufficient radio frequency (RF) power and capacity to support millions and potentially billions of users and devices on the ground both in terms of direct connectivity and backhaul provision.

This only makes sense if this connectivity can be delivered at equivalent or preferably lower cost than other options. NEWLEO Investor presentations and regulatory filings are predicated on the assumption that delivery costs can be reduced to the point at which the presently disconnected, which apparently totals 35 million people in the US and three to four billion people worldwide, can be connected cost effectively

Quite what this means is open to debate. For many of the presently disconnected living on a dollar or less a day, the notion of owning an Apple iPhone 10 at $1000 dollars remains a remote possibility. However the costs reduce assuming Wi-Fi can be used from a low cost solar powered cell site serviced from a NEWLEO constellation. Additionally the NEWLEOS can argue that the subsidies presently going into rural fibre roll out could be spent more effectively on space based systems which presently receive less than 1.5% of government subsidy budgets on a global basis.[[17]](#footnote-17)

There are also potential performance gains in terms of long distance latency. Iridium has successfully deployed a low count LEO constellation (66 satellites) which has been providing service now for over twenty years with an ongoing constellation upgrade now in process (more on this in later chapters). The constellation uses intersatellite switching in K band between 23.187 GHz and 23.387 GHz.

Intersatellite switching has the benefit of reducing the number of earth gateways needed but also provides absolute control of the end to end channel with reduced latency and minimal and known latency variability (also known as latency jitter). This makes Iridium well suited to a number of higher added value military and safety critical payloads.

LEOSAT has a similar constellation proposal to Iridium based on the same space system platform provided by Thales but utilising 7 GHz of paired spectrum (3.5+3.5 GHz) at Ka band for individual user uplinks and downlinks (compared to 10+10 MHz of paired spectrum in L band available to Iridium) and optical inter satellite switching. The FCC filing is based on 120 to 140 satellites in a similar polar orbit to the Iridium Next Constellation. The business model is however focussed on delivering a performance gain over long distance fibre based on the fact that radio and light waves in free space travel faster than radio and light waves in fibre. Over distances of more than 10,000 kilometres this speed advantage outweighs the additional route length (the earth to space, space to earth hop) providing a latency gain for high value applications such as high frequency trading, the oil and gas industries, corporate networking and government agencies (See Chapter 3 for more detail). LEOSAT are working with the European Space Agency on 5G and satellite ‘transversal activities.[[18]](#footnote-18)

Iridium could potentially use their Ka band gateway uplink and downlink spectrum to deliver a similar offer though this would require regulatory approval. Space X similarly are proposing intersatellite switching using optical transceivers which would deliver similar latency gains which could be uniquely useful in a number of global vertical markets including for example automotive connectivity and autonomous and semi-autonomous cars, trucks and transport systems.

**1.8 Regulatory and competition policy**

This brings us to related issues of regulatory policy and competition policy and operator competitive positioning. The established GSO operators have been working in some cases for over fifty years to consolidate their regulatory position both in terms of spectral assets, orbital rights and landing rights.

Low earth satellites conveniently and inconveniently fly through the earth to space and space to earth path of GSO and MEO satellites and potentially pour unwanted RF energy into satellite dishes on earth pointing upwards at the same bit of sky.

This is not a problem for Iridium and Globalstar (who have also operated a LEO constellation for the best part of twenty years) because they have user links in L band and in the case of Iridium, military payloads which justify spectral access priority.

The NEWLEOS are by contrast deploying in Ku, K and Ka band in either the same pass band as GSO operators or in adjacent spectrum. The NEWLEOS are required to provide detailed evidence that sufficient mitigation measures are in place to meet the agreed protection ratios awarded to existing users of the spectrum.

This is achieved through angular power separation and power control mechanisms which we cover in later chapters. The modelling used in these submissions is however open to technical and legal challenge particularly when multiple high count NEWLEO operators or potential operators need to be accommodated. NEWLEO operators may also question each other’s modelling methods which would weaken their position in relation to MEO and GSO operators.

In terms of commercial tension, the NEWLEO business models are predicated on rapid price declines based on assumed and projected rapid cost declines. By contrast the GSO business models and MEO business models (03b being one example) are based on relatively high price points with margins that provide adequate but not always generous cover for debt financing.

One solution would be for one or more of the NEWLEO entities to merge with one or more of the GSO and MEO operators. This could be technically compelling but existing GSO and MEO operator bond holders need to be persuaded that higher gearing and increased implementation risk is worthwhile.

There may also be a nagging doubt that a merged entity could find that their spectral access rights, orbit rights and landing rights could be open to legal challenge which would be an alarming prospect. Some combination of these concerns is probably the explanation for the failed merger between OneWeb and Intelsat.

**1.9 A Brief Summary of Orbit Options and Performance Comparisons**

Just as a reminder it may be useful just to recap on the differences between LEO, MEO and GSO orbits.

Satellite orbits can be categorised as follows:

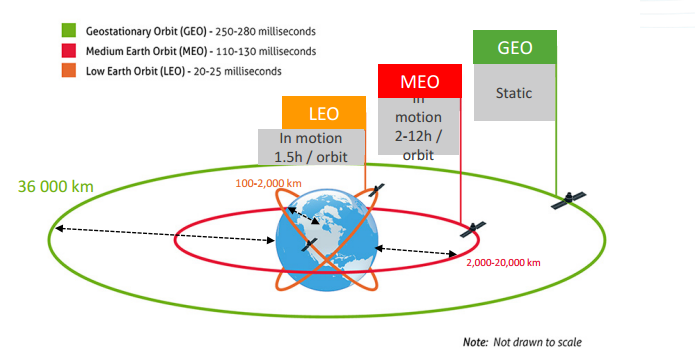
**Table 1.1 Satellites with Altitude**

|  |  |  |  |
| --- | --- | --- | --- |
| **LEO** | Low Earth Orbit | 160 - 2,000 km | 99 - 1,200 miles |
| **MEO** | Medium Earth Orbit | 2,000 – 20,000 km | 1,200 – 12,000 miles |
| **GSO**  **(GEO)** | Geostationary Orbit  (Geostationary Earth Orbit) | 36,000 km | 22,000 miles |

For the sake of completeness we should also reference Highly Elliptical Orbits (HEOs) such as the Tundra and Molnya orbits[[19]](#footnote-19) though these orbits are best suited to high latitude and polar coverage and quazi zenith constellations where some of the satellites are geo synchronous but not geostationary, a GNSS back up constellation over Japan is one example.[[20]](#footnote-20)

Our principle interest for this book is however the LEO, MEO and GSO options. Inmarsat provide this nice graphic comparing the characteristics of the three orbit options including typical latencies and orbit duration.

**Figure 1.1 LEO, MEO and GSO orbits- with thanks to Inmarsat**

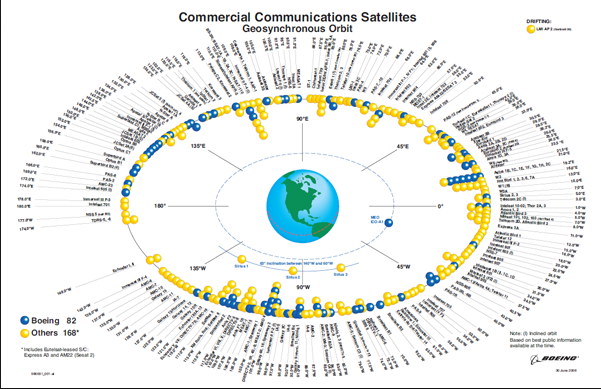


The three orbital categories are generally used for different purposes:

**GSO orbits** are aligned with the equator, and satellites in these orbits will appear to be suspended motionless above a point on the earth. These orbits are therefore useful for providing TV coverage and for weather observation. ‘Spot’ beam antennas on the satellites can be used to provide coverage over specific areas of land or sea. Communications satellites in these orbits can provide good coverage but the high path loss (a function of the high orbit) means that data rates are generally low and only suitable for voice and low-speed data.

The constraint for GSO systems is the finite number of orbital slots, as shown below:

**Figure 1.2 GSO Orbital Slots**[[21]](#footnote-21) **With thanks to the Boeing Corporation**



The amount of orbital separation, set by the ITU used to be 3 degrees (120 orbit slots) and is now 2 degrees (180 orbital slots).[[22]](#footnote-22) Any two GSO satellites are separated from each other by about 75 kilometres (45 miles) just slightly more than the diameter of Greater London.[[23]](#footnote-23)

Capacity can be increased by increasing the RF power and bandwidth of each satellite but this requires larger satellites. Present limits to rocket technology make it hard (expensive) to increase the weight limit much beyond 6,000 kg[[24]](#footnote-24) (though 10,000 kg payloads are possible). Co-located satellites (satellites that appear to be in the same place when viewed from earth) increase GSO capacity and ‘buddy sats’ are now proposed in which additional satellites are sent to dock with existing satellites, doubling capacity and power for each unit addition. Work by DARPA developing the capability to perform through life repair, maintenance and hardware upgrades of GSO satellites[[25]](#footnote-25) could also substantially improve GSO delivery economics.

**MEO orbits** (sometimes called intermediate circular orbits [ICO]) are most commonly used for navigation, environmental monitoring, and some communications satellites. The orbital periods of MEO satellites range from about 2 to nearly 24 hours[[26]](#footnote-26).

The most well known and most widely used MEO constellations are the GNSS constellations. Very few of us drive anywhere without being connected to a satellite network. We take GPS, GLONASS, BeiDou and (in the future) Galileo for granted but the GNSS MEO orbit constellations at 20,000 kilometres are all spectacular examples of contemporary space engineering.

The O3b system is an example of a MEO communications system: satellites orbit at a height of 8,000 km.

**LEO orbits** are used for higher-bandwidth communications satellites (taking advantage of the shorter path and hence lower signal path loss), and for environment-sensing and other scientific satellites which (using a polar orbit) repeatedly circle the earth to build up detailed maps of particular parameters[[27]](#footnote-27).

Typical orbit heights for LEO communication systems are as follows:

**Table 1.2 Orbit altitude comparisons**

|  |  |
| --- | --- |
| Orbcomm | 775 km |
| Iridium | 780 km |
| OneWeb | 1200 km |
| Globalstar | 1410 km |

LEO systems do not have any orbit slot constraints or indeed size and weight constraints. The International Space Station for example in orbit at 400 kilometres is the size of a football field and weighs 408,000 kg though of course was built over a long period at significant expense. Note that the ISS communicates with earth via the NASA (GSO) Near Earth Network so is an early (1998) example of a mixed constellation LEO/GSO constellation.

Satellites have to obey the Newtonian Laws of Physics so satellites closer to the ground will be travelling faster. More satellites are needed in low earth orbits to provide equivalent coverage to MEO and GSO satellites. So for example Iridium satellites travel at 17,000 miles per hour (27,000 kilometres per hour) and have a horizon to horizon transit time of 8 minutes. For 70% of the time there will be more than one satellite in view.

GPS satellites travel at 8,700 miles per hour (14,000 kilometres per hour). The higher speed of the Iridium satellites gives them a stronger Doppler signal. When combined with a higher flux density (i.e. signal strength) at ground level this provides an alternative time and location system known (unsurprisingly) as the Iridium Satellite Time and Location System.

Satellites today include Pico satellites weighing less than 1 kg, Nano satellites weighing less than 10 kg, Micro satellites weighing between 10 and 500 kg and Macro satellites (>500 kg)

**Table 1.3 BIGSATS SMALLSATS**

|  |  |  |  |
| --- | --- | --- | --- |
| Pico Satellites (Cube sats?) | Nano Satellites | Micro Satellites | Macro Satellites |
| <1 kg | < 10 kg | < 500 kg | ≥ 500 kg |

Inmarsat I-5 Ka band satellites for example are (big) macro satellites with a launch mass of 6100 kg, the body height of a double decker bus, a solar array wing span of 33.8 metres generating 15 kilowatts of power and a xenon ion propulsion system for in orbit manoeuvring.

The economics of delivering large and small satellites into space are being transformed by launch innovation, for example reusable rockets from Space X, Europeanized Soyuz rockets and electric satellites (launched into interim orbits before floating up to their final orbit). Satellites are lasting longer and can potentially be refuelled and repaired in space.

**1.10 Satellite Technology Innovation- Fractional Beam Width Antennas**

The topic of technology innovation is a critical thread through this Chapter and all subsequent Chapters. One important innovation we will be looking at is fractional beam width antennas, antennas with a 3dB beam width between 0.5 and 1.5 degrees implemented typically as 12 to 100 spot beam arrays.

At this point it is worth highlighting the difference between fractional beam width antennas and MIMO systems. Both approaches require highly linear transmit and receive paths to support phase shifting, both require adequate wavelength spacing between antennas but everything else is different.

MIMO systems are configured to produce multiple paths with each path separately modulated and channel coded (and amplified) to support high per user data rates with adequate multiplexing efficiency over short distances. Fractional beam width antennas are configured to deliver link budget gain from single narrow beam paths between a base station and user/IOT device.

MIMO systems exploit multi path. Fractional beam width antennas minimize multi path (and the associated delay spread). A well designed fractional beam width antenna can produce more than 40 dBi of isotropic gain – the primary objective is to support moderately high data rates over long distances rather than super high data rates over short distances. Fractional beam width antennas are the single most important technology enabler for present generation of high throughput (HTS) satellites. They are used to focus ‘on demand’ RF energy on small geographic areas.

Fractional beam width antennas can also be used in terrestrial networks to focus ‘on demand’ RF energy on individual users or IOT devices. Used in conjunction with angular power separation techniques, covered in more detail in later chapters, these antennas are an important technology enabler for cost economic power efficient wide area high data rate high mobility 5G networks.

**1.11 FDD dual use dual band spectrum with fractional beam width antennas**

The other important difference between MIMO and fractional beam width antennas is that MIMO is more efficient when implemented in TDD spectrum as the uplink and downlink are reciprocal.

However TDD systems do not deliver the same sensitivity as FDD systems and get less sensitive and less efficient with distance. In other words TDD systems do not scale efficiently in wide area networks and only work adequately well if all operators are co sited which given present competition policy is largely impractical. The same applies in the satellite sector.

A typical Ka-band satellite FDD band plan at 28 GHz has four 250 MHz uplink channels between 28.35 GHz and 30 GHz paired with a downlink between 17.7 and 21.2 GHz. This is matched to a military band uplink at 30 to 31 GHz and a military down link at 20.2 to 21.2 GHz

The Ka-band payload of an Inmarsat Global Express satellite can be switched between military and commercial frequencies with the military bands supporting a range of high added value applications including unmanned aerial vehicle (UAV) connectivity and control.

**1.12 Present Launch Plans – Intelsat and Eutelsat**

In 2009, Intelsat announced a $3.5 billion fleet investment and a hosted payload agreement with the Australian defence force followed in 2012 by plans for a new generation (known as the EPIC generation) of high throughout (HTS) satellites. Two of these 6500 kg satellites, built by Boeing, are capable of being launched from a single Ariane 5 rocket. The satellites are initially planned to have Ku band transponders with services being targeted to aeronautical and maritime markets, treading on Inmarsat’s traditional stamping ground.

Eutelsat have a 44 transponder Ku band electric satellite (Eutelsat 7C) planned for launch in the third quarter of 2018 optimised to provide service to sub Saharan Africa and a Ka band satellite built in Israel called AMOS (Affordable Module Optimized Satellite but also a Jewish prophet) to be launched on a Space X rocket from Cape Canaveral.

Facebook have announced an agreement with Eutelsat to use this satellite to provide low cost internet access to Africa using six of the AMOS Ka band spot beams. The satellite GSO orbit at 4 degrees west will also provide coverage for the Middle East, Western, Central and Eastern Europe though some country specific landing rights issues will need to be resolved.

**1.13 People and politics in the satellite industry**

This brings us to politics and the people behind the politics and back to the 2016 American Space Renaissance Act proposed by Congressman Jim Bridenstein, a Congressman from Oklahoma, home of the Oklahoma Air and Space Port.[[28]](#footnote-28)

The Act envisions a renaissance of the military, civil and commercial US space industry. Citing Mr Putin’s investment in Glonass, Mr Bridenstein makes the American case for military investment in ‘the ultimate military high ground’, the need to invest in civil space missions including a Mars mission (27 NASA space missions have been cancelled over the past twenty years at a cost of $20 billion) and a favourable regulatory environment for Mr Musk at Space X and Mr Branson at Virgin Galactic and their fellow travellers. A significant number of Republican congressmen and senators are also apparently still planning to launch Mr Trump into deep space at the earliest opportunity.

The bill is supported by EchoStar owned by Charles Ergan who also owns Dish Networks and bought $1 billion par value Light Squared stock in 2013 at a deep discount following the Light Squared Chapter 11 filing in May 2012. As with the early years of the competitively regulated cellular industry, individuals can make a major market impact and a not inconsiderable fortune, Craig Mc Caw being a notable example.

Mr McCaw was a founding investor in the Teledesic satellite project, a planned constellation of low-Earth orbit (LEO) satellitesoperating in Ka-band (30GHz uplink/20 GHz downlink) with the mission to deliver low cost internet connectivity from initially 840 satellites (1993) and then 288 satellites (1997). Teledesic closed down in October 2002 having spent the best part of $1 billion dollars. The spectral and orbital asset rights were acquired later by Greg Wyler for the 03b MEO network now owned and managed by SES.

Light Squared by comparison, the company set up in 2010 to implement an L band hybrid terrestrial satellite network has re-emerged from Chapter 11 as Ligado, the Spanish for connected, chaired by Ivan Seidenberg, the former Chairman and CEO of Verizon and Reed Hundt, former Chairman of the FCC. The name at least suggests a Latin American low cost inter connectivity business plan.

**1.14 Third time lucky for hybrid satellite terrestrial networks?**

The reappearance of Light Squared could be interpreted as a positive indication that hybrid terrestrial satellite networks could be on the agenda again. However Ligado is not being positioned as a hybrid network. There are existing examples of hybrid networks such as Thuraya (GSM+ satellite) which are technically and commercially successful but only in high ARPU countries with large amounts of desert. There are also VHF satellite systems such as Orbcomm providing IOT connectivity that could potentially be combined with terrestrial cellular networks.

Dish Networks has applied for a patent for reusing frequencies between satellite and terrestrial systems based on MIMO and beam forming. Dish is part of a coalition of ten companies that is lobbying the FCC to reallocate 500 MHz of presently unused Non Geostationary Orbit Fixed Service Spectrum (NGSO FSS) between 12.2 and 12.7 GHz (the lower end of Ku band) for ‘5G’ Multi-Channel Video Distribution and Data Services (MVDSS).

This would reduce the NGSO allocation to 11.7 to 12.2 GHz though this is being contested by Space X, One Web LCC and Intelsat. One Web, based in the Channel Islands raised $500 million in June 2015 and partnered with Airbus to build 900 low earth orbit satellites to be launched on Soyuz rockets in 2018 and 2019 though an additional $2.5 billion (and an operating license) will be needed to make this viable. Space X has similar plans to build a constellation of 4000 Ku and Ka-band satellites.

**1.15 Scale and standards bandwidth**

Many thousands of engineers spend many hundreds of thousands of man hours producing 5G standards and specifications documents. The satellite industry is however two orders of magnitude smaller and therefore has significantly less ‘standards bandwidth’ available.

Apart from satellite TV with DVB-S as a relatively widely adopted standard in Europe and Asia, the satellite industry is dominated by proprietary physical layers with minimal overlap with present terrestrial cellular radio standards. Within ETSI, efforts were made ten years ago to support UMTS/IMT-2000 interoperability with satellite systems at 2 GHz adjacent to terrestrial cellular Band 1 but little progress was made. Market presentations about LTE and satellite integration are statements of intention rather than imminent reality. However we would argue that 5G needs the satellite industry. The satellite industry doesn’t need 5G but that is not to say that 5G/satellite integration would not be mutually beneficial.

5G needs the satellite industry because economic wide area high data rate high mobility connectivity can only be achieved by using techniques such as adaptive fractional beam width antennas that are already deployed in the satellite sector. Economic wide area high data rate high mobility connectivity can only be achieved by using spectrum already used by the satellite industry.

**1.16 Channel bandwidths and pass bands – satellite and 5G band plan implications**

This becomes obvious when channel bandwidth requirements are considered.

As per user data rates increase, wider channel bandwidths are required to maintain multiplexing gain. However wider channel bandwidths reduce RF efficiency particularly in space constrained user devices.

So for example in an ideal world, antennas would work over a bandwidth of 10% of centre frequency and filters would work over 4% of centre frequency.

These ideal bandwidths are often exceeded. With antennas this is achieved by changing the electrical length of the antenna or increasing the physical length (for example a PIFA antenna)[[29]](#footnote-29) but in both cases there will be an efficiency loss. With RF filters, wider pass bands soften the filter edges and increase the amount of adjacent channel leakage and inter and intra system interference. This can be mitigated by introducing additional filters, roofing filters as one example, but these increase insertion loss and take power out of the mobile uplink link budget.

The get out clause is that it is not the channel bandwidth that is important but the channel bandwidth as a ratio of the centre frequency.

RF filters are the reason that pass bands in cellular FDD networks below 1GHz are typically not more than 40 MHz (4% bandwidth ratio) supporting some combination of 5 MHz and 10 MHz LTE channels. The expectation within LTE Advanced is that pass bands of 100 MHz will be needed to deliver an adequate compromise between multiplexing gain and RF efficiency. 100 MHz at 3 GHz is an efficient (3.3%) bandwidth ratio.

There is some consensus that an initial 5G network deployment in 2020 will need a channel bandwidth of 250 MHz to deliver adequate multiplexing efficiency. If spectrum continues to be auctioned on the basis of four operators per band this implies a pass band of 1 GHz.

This means that the centre frequency will need to be somewhere close to 30 GHz. This coincides with the spectrum presently being used by Ka Band HTS satellites. Anything much below this would compromise RF efficiency.

By 2025 a channel bandwidth of 500 MHz implies a pass band of 2 GHZ increasing to 1 GHz by 2030 implying a pass band of 5 GHz. This bandwidth is only practical from an RF efficiency bandwidth ratio perspective using the millimetre band, with the spectrum either side of automotive radar being a potential option.

Automotive radar is being implemented between 77 and 81 GHz leaving 5 GHz pass bands either side between 72 and 77 GHz (immediately adjacent to the newly designated US unlicensed band between 64 and 71 GHz) and 82 to 87 GHz. This assumes that in ten years’ time, digital signal processors will be capable of handling 1GHZ channel bandwidths and 5 GHz pass bands power efficiently across a dynamic range of 100 dB. Given that the automotive industry has a similar problem to solve, it will probably happen.

Ku-band is a possible alternative to Ka band and has the advantage of a lower fade margin but it is currently hard to see how these proposals could scale globally. The pass band of 500 MHz potentially available at 12 GHz is also arguably insufficient if a multi operator auction model is required. A 1 GHz pass band at 12 GHz, assuming it could be made available, would result in a loss of RF pass band efficiency.

By contrast, the 28 GHz band is conveniently allocated on a 250 MHz channel raster within a 1 GHz pass band with an efficient (2.5%) bandwidth ratio. The band has established scale in fixed link terrestrial hardware which could be translated into low cost 5G hardware. 28 GHz is therefore arguably an optimum technical and commercial start point for 5G deployment with 38 to 40 GHz as a second alternative.

Later deployments based on 500 MHz and 1 GHz channel bandwidths within a pass band of 4 or 5 GHz are going to be technically more efficient at millimetre wavelengths at 70 and 80 GHz.

It is difficult to see how 5G can be deployed cost efficiently and power efficiently without borrowing from present satellite technologies and without initially using satellite spectrum in the centimetre band (Ka band and possibly Ku band) and longer term in E band, V and W band (the millimetre band).

AT&T announcements with EchoStar and Verizon and Viasat and Facebook and Eutelsat are an early sign of this emerging dependency and appear to be validated by a shift in US spectrum and competition policy.

This shift is not reflected in present ITU spectrum or standards policy and needs to be factored in to future competition policy. Satellite operators have by and large been gifted their spectrum and typically have access to at least 4 GHz of aggregated bandwidth (including L band and C band allocations).

It will however be a delicate balancing act to arbitrate what are likely to be complex coexistence, co-sharing cooperation and commercial challenges and opportunities between the 5G community and satellite industry. The complexity will likely be compounded by the US taking a significantly different approach to the rest of the world in terms of regulatory and competition policy. The 28 GHz band would appear to be particularly well suited to initial 5G deployment but will be politically challenging if global scale is to be achieved.

**1.17 Impact of NEW LEO deployments – the progressive pitch sales pitch**

From a regulatory perspective, satellites are divided into geostationary (GSO) and non-geostationary (NGSO). The ITU specifies that GSO satellites have priority over MEO and LEO (NGSO) satellites with regard to frequency usage. LEO satellites in (more or less circular) polar orbits between 160 and 2000 kilometres pass regularly between users and gateways on the ground and MEO and GSO satellites and therefore have to prove that they meet agreed coexistence criteria.

Over the past twenty years Iridium and Globalstar have shown that it is eminently possible for LEO and MEO and GSO constellations to coexist but this is on the basis of narrow band (10+10 MHz) user links in L band.

Iridium mitigate gateway to gateway interference in Ka band by using inter satellite switching (between 23.187 GHz and 23.387 GHz). LEOSAT are proposing a similar approach using the same Thales based platform as Iridium. Some of the proposed new LEOS such as the Space X constellation propose to inter satellite switch using optical transceivers.

The substantive difference between Iridium and NEW LEO operators such as Space X, One Web and LeoSat is the use of Ku band for ground to space and space to user links.

OneWeb acquired the spectrum and access rights owned originally by Skybridge Incorporated, a US entity established in the 1990’s to roll out a high satellite count LEO constellation. The Ku pass band for the downlink is between 10.7 and 12.7 GHz and the uplink is 12.75-14.5 GHz. The gateway downlink pass band is 17.8-20.2 GHz with the downlink at 27.5-30 GHz. In the original FCC filing, Skybridge proposed to meet the US Ku-band EIRP and flux density limits and protection ratios to the shared services supported in and adjacent to the pass band by using progressive pitch angular power separation.

This means that as the satellites move towards the equator they deliver their power at a progressively more inclined angle to avoid sending power into GSO satellite receivers pointing directly upwards. As they move away from the equator the power is delivered more directly downwards on the basis that GSO satellite dishes will be pointing at a progressively lower elevation.

This is achieved by slowly rolling the satellite in one direction then reversing the roll after passing the equator and switching off transmission when directly overhead. Given that the orbit time is 110 minutes this happens every 55 minutes using reaction or momentum wheels powered from the solar panels on the satellite, a simple but clever system. We revisit this in more detail in Chapter 7 (Constellation Innovation).

The FCC was subjected to significant lobbying from other incumbent users in the Ku user and Ka gateway pass bands with the methodology used to calculate interference levels cited as a major concern.

Twenty years on these arguments continue. OneWeb, Space X and LEOSAT stress that their progressive pitch approach coupled to adaptive power control and in some case fractional beam width adaptive antennas is significantly more effective than the original Skybridge (and Teledesic) proposals but the modelling is significantly complex, particularly when multiple constellations sharing the same pass bands have to be taken into account. There are also a wide range of potential victim receivers ranging from high definition and UHD satellite TV, very small aperture terminals and a wide mix of civilian and military two way radio systems.

Conversely if relatively extreme inclination angles are imposed on the NEWLEOS, there will be a directly adverse impact on the link budget, additional latency and a capacity cost all of which will subtract value from the NEWLEO business model.

There is another potentially tricky aspect to the progressive pitch sales pitch. If the NEWLEOS can demonstrate that they can coexist with GSO operators in the same pass bands then it could also be assumed that the spatial separation and power techniques used to achieve this could be equally effective in allowing 5G operators to co share the spectrum, including for example the 28 GHz band.

This could form the basis of some interesting technical and regulatory arguments at WRC 2019 and brings us back to the topic of regulatory and competition policy.

**1.18 Co-existence and competition, subsidies and Universal Service Obligations**

We have said that spectrum access rights and in the satellite industry, orbit access rights and landing rights are conferred on the basis of expected and promised social and economic benefits from improved connectivity. This could either be benefits delivered to consumers or corporate and industrial users, public safety and disaster relief and emergency services or to military and defence communities. The promised benefits are predicated on various combinations of technology and commercial innovation or improved exploitation of the underlying properties of a delivery medium.

For example, LEOSAT has a distinctive business model based on the proposition that radio waves move faster in free space than light in fibre. Combined with inter satellite switching, this means that over distances of more than 10,000 kilometres, LEOSAT can demonstrate a latency gain which can potentially realise high value from applications such as high frequency trading and other time critical financial services. Complete control of the end to end channel also minimises jitter and maximises security.

By contrast, OneWeb and Space X in their FCC filings stress their potential role in connecting the unconnected or under connected. Depending on how you count them this amounts to about 35 million people in the US and 3 to 4 billion people globally.

Greg Wyler, the founder of 03b, (the **O**ther **3 B**illion) successfully used this argument to gain regulatory approval for the O3b MEO constellation in 2008 having acquired Ka band spectrum from Teledesic when it stopped constellation development in 2002. This provided O3b with access rights to the downlink pass band between 17.7 and 20.2 GHz and an uplink between 27.5 and 30 GHz, the same bands that are proposed to be used for the NEWLEO Ka band gateway uplinks and downlinks and already used by Iridium and a number of GSO operators.

03b inconveniently had to raise capital in the year that Lehmann brothers went bankrupt and it is a tribute to the persuasive skills of the Wyler management team that the constellation launched and more or less met its business plan objectives. However it achieved this by substantially changing the market focus of the business which now supplies internet connectivity to cruise ships 40 degrees either side of the equator.

This highlights the problem that many of the presently disconnected are low income or no income customers so making any comprehensive inroads into the digital divide is likely to require substantial government subsidy on a country by country region by region basis.

This already happens with terrestrial fibre subsidies or via universal service obligations imposed with various financial incentives. The amount of digital divide subsidy going to the satellite industry is relatively small (of the order of 1.5% in the US market) and the NEW LEO contenders including Space X make a persuasive argument that these dollars would be more effectively spent with them rather than on terrestrial system subsidies.

Whether this is the case depends on the fine detail of the final agreements on coexistence with the agreement process now made more complex by the ambitions of the 5G community to share or acquire Ku and Ka band spectral assets.

This includes a growing recognition by aspiring 5G operators that the principle of angular power separation could be applied to support co sharing between terrestrial 5G and LEO, MEO and GSO networks, a combination which would provide superlative global coverage and capacity gain achieved through spatial frequency reuse.

There are however substantial regulatory barriers that need to be overcome before this becomes a practical proposition. The failure of the proposed Intelsat and OneWeb merger provides a case in point. It may have been that the Intelsat bond holders were wary about increasing their gearing ratios, already stratospherically high. It may also have been influenced by a nagging worry that Intelsat’s spectrum and international landing rights, patiently negotiated over 50 years, could have been open to legal challenge if the merger had gone ahead.

It may be that this particular log jam will be unlocked by Google or Facebook. As stated earlier Google and Fidelity Investments already have a 10% stake in Space X in return for a $1 billion dollar investment and both companies have enough spare cash to buy a large part of the satellite industry at present enterprise value. They also have substantial regulatory influence.

In the meantime it is important that the NEW LEOS do not shoot themselves in the foot by disputing each other’s interference models and offer a unified vision to regulatory authorities around the world based on the thesis that high count low earth orbit satellite constellations have a critical and economically compelling role to play in future internet connectivity and can and should be seamlessly integrated with MEO, GSO and terrestrial 5G networks.

**1.19 US Competition and spectral policy**

In April 2016, AT&T and EchoStar announced a potential sharing framework for the 28 GHz band with Hughes Network Systems and Alta Wireless as possible partners. In parallel, Verizon and Viasat agreed to undertake coexistence, co sharing and cooperation studies. This followed the AT&T filing with the FCC in January for an experimental license to conduct fixed and mobile testing with *various types of new wireless equipment* between 27.5 GHz and 28.5 GHz.

The CTIA suggested these studies should be broadened to include Upper Microwave Flexible Use (UMFU) shared access agreements in the 37 to 40 GHz band. In July 2016 the FCC responded by approving its Spectrum Frontiers proceeding releasing UMFU designations for 27-28.35 GHz, 37-38.6 GHz and 38.6-40 GHz and a new unlicensed band at 64 to 71 GHz.

The interest by US and other potential 5G terrestrial mobile operators in the 28 GHz and 38-40 GHz bands is easy to explain. The satellite industry has access to FDD spectrum which is ideally suited to terrestrial 5G implementation. Additionally the satellite industry has successfully implemented fractional beam width antenna technology which meets many and potentially all of the 5G wide area high data rate link budget requirements.

Additional scale economy benefits are also realisable from 28 GHz and 38 GHz terrestrial fixed link hardware. Many satellite operators including South East Asian operators are however opposed to the idea of having 5G in the 28 GHz band and are suggesting that investment in high throughput satellites using or proposing to use this band will be compromised. It is of course not unusual for the US to have a different regulatory outlook and the future of the 28 GHz band will almost certainly continue to be debated vigorously for the foreseeable future.

**1.20 Satellites and local area connectivity**

NEWLEO business models are based on the assumption that Wi-Fi will be used to provide local connectivity from small optionally solar powered low cost base stations and there may be similar opportunities to integrate Bluetooth into these optimized localized delivery systems.

We cover Wi-Fi 802.11, 802.15, proprietary low power drain long distance licensed radio options such as SigFox and Lora and latest iterations of Bluetooth including Low Energy Bluetooth and long distance Bluetooth in the standards Chapter, Chapter 10 but on a general note it can be observed that the integration of local area and personal area networks with 5G and satellite systems will be one of the critical paths to delivering a satisfactory 5G user and IOT experience. Part of the challenge will be managing integration of these enhanced legacy radio systems into low cost small form factor user and IOT devices

Traditionally physical layer design for 3G and 4G networks has been focused on delivering in band spectral efficiency using higher order modulation with substantial envelope modulation. These options trade off in band spectral efficiency against spectral splash into adjacent out of band spectrum. They are also not inherently power efficient.

5G includes waveforms that are sufficiently power efficient and sufficiently narrow band for battery powered IOT applications. These need to be regarded as complementary rather than competitive to other optimized legacy technology options.

In the context of 5G and satellite integration and in an ideal world, 5G and satellite would use the same physical layer or at least share some baseline commonality. This remains possible as the Release 16 and 17 standards process has a measure of flexibility in terms of physical layer implementation for Ku, K and Ka- band though as we highlight in Chapter 10, issues of standards integration are only just now being addressed with significant work still to be done before any meaningful integration is achieved.

It may be more likely that some compatibility can be achieved between the Low Mobility Large Cell (LMLC) 5G physical layer and satellite physical layer particularly as satellites have the potentially useful capability to scale from the typical maximum cell size achievable in terrestrial mobile broadband systems (between 35 kilometres and 100 kilometres) up to cell sizes of 2000 kilometres or more.

**1.21 Summary**

Over the past sixty years there has been a steady consolidation of spectral access rights in the satellite industry scaling from VHF, though L band and S band and C band to Ku, K and Ka band with submissions now being made for V and W band allocations. These spectral access rights are coupled to intensively negotiated orbital rights and country by country access rights.

NEWLEO operators either have to undergo these regulatory processes in a much reduced time scale (5 years rather than 50 years) or merge with established GSO, MEO and LEO operators with existing rights. Such mergers might however be subject to legal challenge and in practice regulatory and competition policy barriers might be more problematic than the technical challenges ahead.

The NEWLEO operators are confident that they can reduce delivery costs by at least an order of magnitude compared to existing operators and can cost effectively provision sufficient capacity to meet the demand that these lower costs points could realise. A fast rate of rate decline would however be problematic for some existing GSO operators who are reliant on generous margins to meet present debt cover commitments.

Cash rich OTT players such as the GAFA quartet could help resolve this commercial tension. An initial investment by the Alphabet Group, the holding company for Google, of £1 billion dollar in Space X suggests a developing interest from web scale majors in the satellite sector.

There are some things that can only be done from a satellite, some things that are better done from a satellite and some things that are better done locally within a terrestrial network.

Superficially it seems daft to send a signal hundreds or thousands of kilometres in to the sky when compared to the option of a base station a few metres away but network densification in 4G and 5G is increasing routing complexity and the cost and power drain of backhaul networks making the end to end journey unpredictable and occasionally expensive.

There is therefore an increasingly persuasive argument that an increasing amount of direct user and device traffic and indirect backhaul traffic in 4G and 5G networks could be carried more cost effectively over satellite networks.

However achieving global coverage requires a mix of LEO, MEO and GSO constellations. Angular power separation potentially allows frequency re use across these multiple constellations and re use for 5G terrestrial point to point and user to base station links but many issues of regulatory and competition policy need to be resolved before this becomes a practical reality.

In particular the satellite industry and satellite industries remain locked into an adversarial spectral allocation and auction process that inhibits and frustrates cooperation between the two operator sectors and their respective supply chains.

This brings us to the subject of our next Chapter, the Race for Space Spectrum and the potential battleground issues that need to be resolved at WRC 2019 and WRC 2023.

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2. https://www.space.com/38314-elon-musk-spacex-mars-rocket-earth-travel.html?utm\_source=notification [↑](#footnote-ref-2)
3. <https://www.blueorigin.com/> [↑](#footnote-ref-3)
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22. http://www.satellitetoday.com/publications/via-satellite-magazine/features/2008/03/01/hot-orbital-slots-is-there-anything-left/ [↑](#footnote-ref-22)
23. https://space.stackexchange.com/questions/2515/how-closely-spaced-are-satellites-at-geo [↑](#footnote-ref-23)
24. The largest GSO satellite is TerreStar-1 (6,910 kg), launched in 2016 on an Ariane 5 rocket [↑](#footnote-ref-24)
25. https://www.darpa.mil/program/robotic-servicing-of-geosynchronous-satellites [↑](#footnote-ref-25)
26. Telstar 1, launched in 1962, orbited in MEO [↑](#footnote-ref-26)
27. A good example of this is the GRACE (Gravity Recovery And Climate Experiment), which has been making detailed measurements of Earth's gravity field anomalies since its launch in March 2002. GRACE uses a microwave ranging system to accurately measure changes in the speed and distance between two identical spacecraft flying in a polar orbit about 220 km apart: small changes in gravitation are detected by minute changes in the distance between the two spacecraft. [↑](#footnote-ref-27)
28. https://airspaceportok.com/ [↑](#footnote-ref-28)
29. http://www.antenna-theory.com/antennas/patches/pifa.php [↑](#footnote-ref-29)