Chapter 7
Traffic Jam Over the Equator

Getting into space is tough.

Gravity tries its best to ensure that what goes up, must eventually come down: the only way to stay up is to move fast enough forward so that the Earth's curvature bends away under you while gravity relentlessly keeps on pulling you towards the Earth. You have to literally keep falling off a cliff, except your cliff is the horizon that you will never reach, as it is curving down in sync with you.

Achieving this endless fall over the horizon requires that the satellite must be accelerated to a speed of at least 8 kilometers per second.

Not per hour or even per minute. *Per second*.

That's like covering the distance between London Heathrow and Paris Charles de Gaulle airports in less than 45 seconds, or crossing the Atlantic from London to New York in just under 12 minutes.

This kind of orbital speed requires vast amounts of energy, and therefore the actual payload of modern rockets is just a tiny portion of the total structure that starts lifting up at takeoff: most of the size and weight is needed for the fuel that accelerates the relatively small mass of the satellite at the top of the rocket. Despite the recent amazing advances in reusable rockets by companies like *SpaceX* and *Blue Origin*, going into space is still a very costly business: the launch costs, even without counting the value of the actual satellite or satellites on board, are well into several tens of millions of dollars.

But the multitude of advantages with having satellites constantly over our heads make all this effort worthwhile, and hence launching satellites has been a booming business over the last fifty years.

There are more than 4,000 active satellites orbiting the Earth at the time of writing this, and about the same number of satellites have ceased to work, either creating a continuously growing set of orbital *space junk*, or being destroyed as spectacular streaks of fire in the sky after re-entering the atmosphere.

P. Launiainen, *A Brief History of Everything Wireless*,
https://doi.org/10.1007/978-3-319-78910-1_7

Anything that remains uncontrollable on orbit needs to be constantly monitored for potential collisions: for example, the only currently manned space station, the *International Space Station* (*ISS*) has to make frequent minuscule adjustments to its orbit in order to avoid hitting these rogue objects that cross its path.

And the number of orbiting satellites is constantly increasing—just one launch by India in early 2017 carried over 100 tiny *nanosatellites* into orbit.

In terms of being able to communicate with the satellites, the huge relative speed between a satellite and any ground station causes certain complications:

Satellites on a *Low Earth Orbit* (*LEO*), which refers to altitudes below 2,000 kilometers, fly around the Earth in less than two hours, repeatedly passing from horizon to horizon over the locations below their orbits. Therefore, having a constant radio connection between a ground station and a satellite requires multiple ground stations scattered around the Earth, so that at least one of them has the satellite in sight. And as the transmission power of a satellite is often very low due to the limited amount of power provided by the solar panels, it is usually necessary to utilize a highly directional, movable antenna that can track the position of the satellite in real-time.

In addition to this, the constantly varying relative speed between a ground station and a satellite in LEO also causes the communication frequencies to shift according to the *Doppler effect*, which has to be continuously corrected for. The positive uses of this effect were discussed in Chapter 6: ***Highways in the Sky***.

All in all, these inherent properties make the process of tracking LEO-based satellites quite complicated.

The very first communications satellite, *Telstar*, became operational in 1962 and enabled intercontinental live television transmissions between Europe and North America, but due to its low-level orbit around the Earth, the intercontinental communications window was only available for 20 minutes at a time, and occurred only once in every 2.5 hours.

Despite this serious limitation, *Telstar* heralded the start of a new Space Age of communications, connecting audiences across continents in real-time. To commemorate this achievement, an all-instrumental pop song carrying the same name was composed by a band *The Tornados*, becoming the first British single that reached the number one position in the USA.

The Space Age had a mind meld with Pop Culture.

The narrow intercontinental transmit window was not the only limitation of *Telstar*: the available transmit power was also so small that the tracking antenna in Andover, Maine had to be enormous, about the size of a bus, and weighing over 300,000 kg. As the position of the satellite changed with a speed of 1.5 degrees per second, the moving antenna platform that was needed for tracking *Telstar* was a mechanical miracle in itself.

There is, however, one orbit that is very special, completely removing the requirement of continuous tracking and the issues of *Doppler effect* in frequency: if you position the satellite at an altitude of 35,786 kilometers and align the orbit with the equatorial plane of the Earth, the time it takes for the satellite to do one rotation around the Earth will be exactly 24 hours.

Therefore, the orbital speed of the satellite matches the speed at which the Earth is rotating around its axis, and the satellite seems to remain continuously in the same position relative to the horizon. If you point your antenna towards it once, you do not need to adjust your antenna ever again: whether you are transmitting or receiving, your connection with the satellite remains available from the same fixed location in the sky. And as the relative speed between your antenna and the satellite is zero, there is also no *Doppler effect* to worry about.

An extra bonus also results in from such a high orbit: any satellite at this altitude remains visible from about a third of the Earth's surface at a time. Hence, by putting a transmitter on the satellite, you can theoretically cover all receivers residing anywhere over about a third of the globe in one go. The further North or South you move on the Earth, the lower in the horizon these satellites appear to be, and thus only areas close to the North and South Poles remain outside of the theoretical coverage, most often due to masking high terrain on the horizon.

The application of this kind of *geostationary satellites* completely removes the need for complex, moving antennas that would otherwise be needed to maintain constant communications if the satellites were to reside on a Low Earth Orbit—you only need to align your antenna once and then communicate happily ever after.

The mathematics behind the rotational speeds of various orbits were understood at the beginning of the 20th century, and the existence of such a *geostationary orbit* at roughly 36,000 kilometers altitude had been first noted by Russian scientist Konstantin Tsiolkovsky, who was one of the pioneers in the theory of rocketry. The first reference to the potential of this kind of orbit for communications purposes can be found in a book by another early pioneer of rocketry, Slovene Herman Potočnik, published in 1928, just one year before his unfortunate early death at the age of 36.

The very first in-depth discussion on the benefits of a geostationary orbit for wireless relays and broadcasting purposes can be traced back to an article entitled *Extra-Terrestrial Relays—Can Rocket Stations Give Worldwide Radio Coverage*, published in the *Wireless World* magazine in 1945. It was written by a young British engineer called Arthur C. Clarke, who later became a very prolific *Science Fiction* writer, correctly predicting many future developments, as will be discussed in Chapter 8: ***The Hockey Stick Years***.

Clarke's article came out in the post-Second World War era, at a time when there was already a glimmer of hope of achieving real space flight, thanks to the war-time experiences with the German *V-2* ballistic missiles. But as the state-of-the-art in wireless communications was still based on vacuum tube technology, Clarke's solution expected that maintaining such relaying space stations in working condition would require constant human presence in orbit.

It took almost twenty years until the first practical application of the geostationary orbit was finally in place: the *Syncom 3* satellite proved the usefulness of such a setup by relaying live television broadcasts from the 1964 *Summer Olympics* in Tokyo to viewers in the United States. Unlike with *Telstar*, the intercontinental connectivity provided by *Syncom 3* was continuous, and there was no need for massive, constantly moving antennas.

A rush to exploit this unique orbit then followed, and the geostationary *Clarke Orbit*, as it is sometimes called, is now getting very crowded: currently there are over 400 satellites circling in sync with Earth‘s rotation over the Equator.

All known satellites around the Earth are beautifully visualized at an interactive website:

http://bhoew.com/sat

The special ring of geostationary satellites stands clearly out from the crowd.

Due to the potential interference between adjacent satellites, their positions, or *slots* as they are called, and the frequencies used for communications, are strictly regulated by the *International Telecommunication Union* (*ITU*).

Many of the geostationary satellites are used for direct broadcast satellite television, but some act as communications links between continents or offer rentable channels for whatever purpose the customer wants to use them.

As an example, most mobile camera crews of live television operations use satellite connectivity to send their field transmissions back to the company headquarters, and most live intercontinental news reports go across at least one satellite on the Clarke Orbit.

Other notable uses for these geostationary slots are weather satellites that can continuously keep track of a third of the Earth’s surface at once, the satellite radio network *Sirius XM* that provides uniform digital audio and specialty data reception of hundreds of channels across the continental United States, *Wide Area Augmentation System* (*WAAS*) support for enhanced GPS precision, as explained in Chapter 6: ***Highways in the Sky***, and inevitably, also several satellites that are used for military communications and surveillance.

The *International Space Station* (*ISS*) is kept on an orbit that varies in altitude between 330 and 425 kilometers, and hence resides on a Low Earth Orbit, but the communications facilities for *ISS* rely on *NASA’s Tracking and Data Relay Satellite* (*TDRS*) system. It is based on satellites sprinkled over the Equator, so that as the *ISS* whizzes around the world in about 90 minutes, there’s always at least one *TDRS* satellite visible and thus available, providing uninterrupted two-way communications with the *ISS*.

Thanks to this high-bandwidth connectivity, there are now *YouTube* channels that provide constant video feed from the activities and views from the *ISS*, easily found with the search term “NASA live stream”.

As mentioned above, there are several weather satellites on the geostationary orbit, and a nice example of the excellent quality of the weather satellite coverage that can be achieved from that kind of vantage point, in real time and recorded in various wavelengths, can be found here:

http://bhoew.com/wea

This website updates every ten minutes, providing the newest picture taken by the Japanese *Himawari* satellite, which covers the globe from Kamchatka Peninsula in the North to Tasmania in the South.

Satellites use *microwave* frequencies for communications, which, due to their high frequency, accommodate a multitude of individual channels into a single transmission beam, for reasons explained in TechTalk ***There is No Free Lunch***.

The flip side of this high frequency is the fact that water absorbs microwaves very effectively, so hard rain or intense snowfall can therefore cause problems in reception.

Further discussion about microwaves can be found in Chapter 11: ***Home Sweet Home***.

Another less obvious issue with geostationary satellites is the fact that any communication with them must be able to traverse a distance of 36,000 kilometers: this is almost one tenth of the distance to the Moon and just 4,000 kilometers short of the circumference of the Earth, and due to the laws of physics, this causes some limitations.

First of all, as the power of your transmitted signal drops to one fourth of its original strength every time you double your distance, you need a lot of transmission power to produce a signal strong enough to be received at the other end. This can be remedied to some extent with highly directional antennas, which are the norm for satellite communications—everyone is familiar with the multitude of television dish antennas scattered around our cities and towns.

Even though it is theoretically possible to cover about a third of the Earth's surface with a single satellite, having a satellite television transmitter powerful enough and with a wide enough beam to achieve this is currently not a viable solution, unless the receiving antennas are enormous. Due to this, the direct broadcast television satellites have highly directional antennas that cover only specific areas of the Earth: typical beams can cover an area the size of Central Europe, for example, and the further away you get from this optimal reception area, the larger your antenna has to be to counteract the reduced strength of the signal.

The second limitation is much less obvious:

Because radio signals propagate with the speed of light (about 300,000 kilometers/s), a distance of 36,000 kilometers is long enough to create a noticeable delay. This delay becomes even more pronounced if you first send the signal out and it then gets beamed back, making a total roundtrip of 72,000 kilometers.

I remember experiencing my first concrete example of the physical limits of the speed of light when I was a kid, watching a documentary that was describing the Canadian *Inuit Broadcasting Corporation (IBC)* satellite television system, which provides television transmissions to the Arctic areas of Canada. The documentary had a section in which there were two television monitors side by side, one showing the uplink transmission that was being beamed to the satellite, and the second one showing the same program as it was received back from the satellite.

Because the total distance from first sending the signal to the satellite and then retransmitting it back was two times 36,000 kilometers, this caused a clearly noticeable delay of 0.24 seconds between the monitors.

This very expensive "delay line" is a good example of how it is one thing to read about theoretical scientific subjects like the speed of light, and very different to see what it means in practice.

Seeing is believing.

For unidirectional broadcast purposes, like transmitting a live sports event across continents, a delay of 0.24 seconds is nothing, and most modern digital television systems easily add more to that due to the extra time it takes to buffer and decode the received signal, but there are many interactive applications where a delay like this becomes noticeable:

Next time you watch a live newscast, note the delay between the question from the studio and the corresponding answer from the field.

The cause of this unnaturally long pause is not due to the reporter having to think hard before responding—it is simply due to the time it takes for the question made in the studio to make its way up to the satellite, bounce off of it to the field crew receiver, and then the same amount of up-down trek again as the field reporter starts to respond to the question.

All in all, this amounts to about half a second, not counting the additional delays in processing the actual digital signal.

If you have a live connection between, say, the United States and Australia, you may end up having multiple hops across several satellites, adding even more delay to the connection.

In any case, you are witnessing a concrete example of the most fundamental speed limit of the universe in action, and for any communications that require interactivity, like simple intercontinental phone calls, this extra delay that is caused by the 72,000 extra kilometers' roundtrip soon becomes very annoying.

To counteract this, the world's oceans are being crossed over and over again by a multitude of *fiber-optic data cables*, which, thanks to their much shorter point-to-point connections, reduce the speed of light delay to levels that have no noticeable side effects in most real-word use cases.

As mentioned, there are only a limited number of interference-free slots available on this geostationary orbit, and due to *solar wind* and minute variations in gravitational forces, some even caused by the masses of neighboring satellites, geostationary satellites need to make repetitive positional corrections in order to remain in the exact location. Eventually there is no longer enough propellant left for these corrections, and the satellite is usually decommissioned by pushing it about 300 kilometers further out to the so-called *graveyard orbit*, so that it won't end up on a collision course with its still-functioning neighbors.

This end-of-life procedure, requiring about the same amount of fuel as three months of normal position keeping on the Clarke Orbit, has been a mandatory requirement for geostationary satellites since 2002, and it guarantees that the satellite can eventually be moved to a location in space in which it is not interfering with other satellites. Despite this regulation and earlier, voluntary approaches to identical end-of-life management of satellites, there are over 700 uncontrolled objects now adrift close to the geostationary orbit, either due to a system failure or by lacking an end-of-life procedure, and they all need to be constantly tracked to avoid collisions.

In most cases, after decommissioning or losing an existing satellite, the freed slot will be taken over by a brand new and much more capable satellite with shiny-new technology, often already planned for this replacement task several years in advance, as these locations are limited and hence very valuable. Handling the allocations of these slots is one good example of successful international collaboration regarding shared "real estate" in space.

Despite its numerous advantages, the geostationary orbit is by no means the only one that is in use for satellite-based communications: if you need to have a handheld system on the ground that needs to be able to communicate with a satellite, the 36,000 kilometers distance requires way too much transmission power, and the delay caused by crossing this huge distance twice may be unacceptable for interactive uses. Therefore, if you want to combine true portability with true global coverage, you need to create a different solution.

Meet *Iridium*—an ill-fated communications phoenix that was way ahead of its time at its launch in 1998, and rose back from the ashes after one of the costliest bankruptcies in history. *Iridium* has satellites orbiting at about 800 kilometers altitude, and it got its name from the fact that the original planned number of required satellites was 77, which is the *atomic number* of Iridium, a silvery-white metal. Even though the number of satellites was eventually reduced before the launch, the catchy name stuck.

Iridium was the brainchild of the notorious *Motorola Corporation* and ended up costing about six billion dollars before it went bankrupt in almost immediately after its commercial launch in 1999. It first continued operating under the American *Chapter 11* bankruptcy protection, until in 2001, a set of private investors bought the rights to the existing system and the orbiting satellites for only 35 million dollars.

This was a very decent 99.4% discount for a fully functional worldwide communications system.

After a couple of mergers to strengthen their financial position, the new owners revitalized the system and are now continuing to offer a satellite-based, portable phone and data service that seamlessly covers the Earth.

Because the original satellite technology is from the 1990s, the supported data speeds are very slow by today's standards, about 2.4 kbps, with a time-based cost of roughly a dollar per minute at the time of the writing, both for data and voice connections, so using *Iridium* is by no means a cheap affair, but if you need true worldwide coverage, this solution works from pole to pole:

An example of a connectivity solution via an *Iridium*-based data link is the setup that has been used to connect the *Amundsen–Scott South Pole Station* to the rest of the world, with parallel *Iridium* modems providing a 28.8 kbps speed—just about on par with the early *acoustic modems*.

Due to its extreme location at the South Pole, the station is not able to have a line-of-sight connection with standard geostationary satellites: it relies on a couple of special satellites which keep on crossing over and under the equatorial plane while still maintaining a 24-hour *geosynchronous* orbit. This provides a high-speed satellite communications window during those periods when the connecting satellite moves to the Southern side of the Equator, hence becoming just barely visible over the horizon as seen from the South Pole.

Most of this kind of high-speed connectivity provided for the Amundsen-Scott South Pole Station comes from a selection of *NASA's Tracking and Data Relay Satellites* (*TDRS*), but as they keep on "wobbling" over and under the equatorial plane, this high-speed connectivity is not available all the time.

Therefore, the *Iridium*-based setup is the only backup link that offers continuous availability, and thanks to recent advancements, the researchers in Antarctica will soon be able to have an upgrade: with its initial stellar debts having been washed away through the bankruptcy fire sale, the reborn *Iridium* company has been profitable enough to start renewing their satellites with the latest communications technologies, and as a result, is able to offer considerably improved communications capabilities.

The maximum data speed for the new *Iridium Next* system and its totally revamped *Iridium OpenPort* data configuration will increase to 512 kbps. Existing *Iridium* handsets and modems will continue to work with the new satellites, but with the state-of-the-art satellite technology and matching new devices, *Iridium Next* will be able to offer not only higher data speeds but also many new features, like 64 kbps broadcast mode for multiple devices, together with live tracking support of ships and airplanes.

The first user of the new real-time airplane tracking feature offered by *Iridium* is *Malaysian Airlines*, which is still reeling from the unexplained disappearance of their flight *MH 370* in 2014.

The first batch of these new *Iridium Next* satellites was launched in January 2017, on a much-anticipated launch of the *Falcon 9* rocket by *SpaceX* after the spectacular explosion that destroyed the previous one in late 2016.

This time, though, everything went by the book, including the soft landing and recovery of the *Falcon 9* first stage, and most importantly, having ten new *Iridium Next*-satellites on their expected orbits.

Iridium has also achieved another, not-so-positive history first: in February 2001, one of the *Iridium* satellites collided with a defunct Russian *Kosmos 2251* satellite. The relative speed of these two satellites at the time of impact was estimated to be roughly 35,000 kilometers/h, and the collision created an enormous and potentially destructive debris field in orbit. This event shows the importance of tracking all objects in space: the worst-case result from a set of collisions is a chain reaction that could destroy tens of other satellites and make huge parts of potential orbits unusable for decades.

The original *Iridium* system has one interesting and surprising unplanned side effect: because the microwave antennas on the satellites are large, polished slabs of aluminum, in the right conditions they act as mirrors, reflecting the light of the Sun to locations on Earth which are already in the deep darkness of the night. Therefore, for anyone at the right place at the right time under the clear night sky, this creates an experience of a slowly moving star suddenly becoming visible, bursting into a star brighter than any other star in the sky for a short while, and then vanishing again.

The occurrences of these *Iridium flares* can be calculated for any location on Earth, and being able to "predict" where and when a "new star" appears can be used as a great source of amazement if you have kids: the website for calculating the timing of Iridium flares for any location on Earth can be found at:

http://bhoew.com/iss

Give it a go, but hurry up—the new *Iridium Next* constellation will no longer have similar antennas, so this free, heavenly spectacular will gradually go away around 2018–2019.

The same website contains tracking information of several other visible satellites as well, including the *ISS*, which is by far the largest object in orbit and hence another impressive sight in the night sky. Its orbit stays fairly close to the Equator, though, and hence it is not visible on high Northern and Southern latitudes.

Another space communications pioneer, *Inmarsat*, has been offering satellite-based voice and data connections since late 1970s. Created originally as a non-profit international organization for maritime use, *Inmarsat's* operational business became a private company in 1999, and has changed ownership several times since then.

The *Inmarsat* solution is based on satellites on geostationary orbits, and the resulting delay means that they are best suited for cases where the delay has no adverse effect, like for email, browsing or unidirectional content streaming. *Inmarsat's* latest high-speed service, *Global Xpress*, has one additional special feature: it offers steerable antennas, allowing highly localized, high-capacity services to be offered on demand on a global scale.

Several companies have been offering satellite-based Internet for decades, including *Inmarsat*, *HughesNet*, *ViaSat* and *europasat*. Some of these companies are also behind the latest fad in intercontinental travel: in-flight Wi-Fi connectivity, as satellites are the only option for seamless communications over the oceans.

Many of these satellite providers are the only Internet connectivity option for rural customers, and usually their plans have some serious limitations in terms of the amount of data downloads that are included in their monthly charges. But as the technology has improved, there is now renewed interest in utilizing the Low Earth Orbit for communications purposes.

Despite its recent upgrades, the LEO pioneer *Iridium's* newest *Iridium Next* incarnation will pale in comparison with the plans that the most versatile innovator of recent history, Elon Musk, has for the next couple of years: his company, *SpaceX*, in not only revolutionizing the launch business with his reusable rockets, but also it plans to implement a LEO-satellite Internet service, *Starlink*, which in its first stage uses no less than 4,425 satellites to cover the globe, expanding up to 12,000 in its final configuration. The tests are due to start in 2018, and the full deployment should be ready by 2024, with the aim of first offering fast Internet access to the United States, and expanding to a global service in later years.

The system is planned to provide gigabit speeds, which would compete with *fiber-optic data cable*-based terrestrial Internet providers, and in order to further improve the throughput of the new system, the satellites also implement a "celestial" *mesh network*, the concept of which is further discussed in TechTalk ***Making a Mesh***.

The plan is nothing short of ambitious, as the number of new satellites would quadruple the current number of existing, active satellites in space, but with his proven technological revolution in electric cars and solar energy systems by *Tesla* and reusable rockets by *SpaceX* in the satellite launching business, Elon Musk's track record gives a lot of credibility to this endeavor. Having giant companies like *Google* and *Fidelity* financially backing his attempt by billions of dollars will also help.

Many traditional aerospace companies, like *Boeing* and *Airbus*, have also presented their satellite-based Internet plans, both privately and in connection with existing players. The resulting competition between all these newcomers and the incumbent players can only mean one thing for us consumers: more products to choose from and more potential for truly universal connectivity, with higher connection speeds and lower prices.

And finally, in the current atmosphere of ever-increasing attempts to discredit scientific approach by so many prominent political leaders, it gives me renewed faith in humanity when billionaires like Elon Musk and Bill Gates put their wealth to work to improve our lives and advance the global reach of technology and health care. This kind of behavior is a fresh, welcome contrast to that of so many recent *nouveau riche* who use their newly-acquired wealth just to buy sports teams with highly inflated price tags.