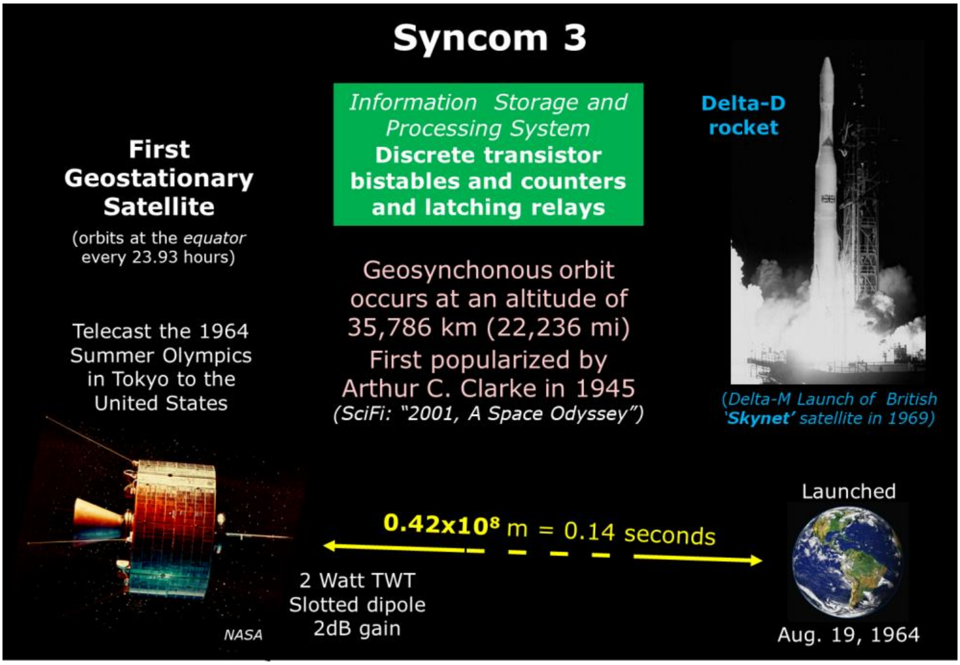
Chapter +8: The Clarke Orbit

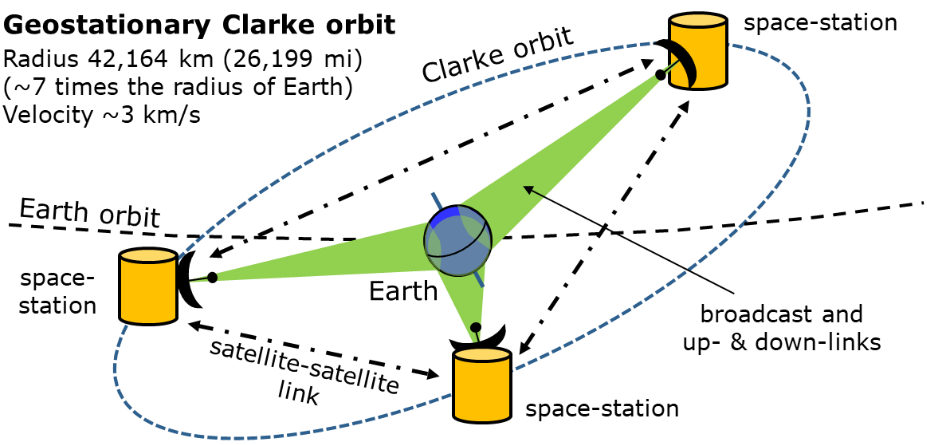


Arthur C. Clark was a true visionary. It was Clark more than anyone else who recognized the importance of the geostationary orbit in global telecommunications. The "Clark orbit", as it is sometimes referred to, played an early role in establishing global telecommunications and provides the basis for all satellite television broadcasting around the world. It also provides internet access to many hundreds of millions in less accessible regions. While, strictly, Clark may not have been the first to recognize the idea of a geostationary orbit for global communications, he was certainly the most famous and the most influential. In the public eye, he is best remembered for his writings in science fiction and in particular for the movie: "2001: A Space Odyssey" directed by Stanley Kubrick.

Arthur Charles Clark[1] was born on the 6th December 1917 in Minehead, Somerset, England. Clark's first job, at age 18, was as a civil service pensions auditor in the UK Department of Education – a rather unexciting and inauspicious start to such a stellar career. This situation was not to last for long. Within three years, Britain and Germany were embroiled in the

[1] http://www.clarkefoundation.org/arthur-c-clarke-biography/

Second World War. Clark served in the Royal Air Force where he worked on the development of radar, a decisive factor in the Battle of Britain and also on a radio glide-path aid for aircraft approach, a vital factor in the Berlin airlift that was the salvation of the besieged city shortly after the war.



The Clarke Orbit: as originally envisioned by Clarke, three equispaced geostationary satellites with radio links between satellites would provide a world-wide communications capability. Because of the need for constant maintenance, (constantly replacing failing vacuum tubes, long before the days of transistors), it was assumed that the satellites would be manned.

In October 1945, Clark published an article in Wireless World entitled "“Extra-Terrestrial Relays: Can Rocket Stations Give World-wide Radio Coverage?”.[2] This paper spelled out the relationship between orbital radius and orbital period and pointed out that at a distant radius of 42,000 km the orbital period is exactly 24 hours. Furthermore, if the satellite lies exactly over the Earth's equator, it will appear stationary with respect to the rotating Earth. Quoting from Clarke's article:

> *"A body in such an orbit, if its plane coincided with that of the earth's equator, would revolve with the earth and would thus be stationary above the same spot on the planet. It would remain fixed in the sky of a whole hemisphere and unlike all other heavenly bodies would neither rise nor set."*

[2] https://web.archive.org/web/20061107121143/http://www.sciencemuseum.org.uk/on-line/clarke/ww2.asp

"It will be possible in a few more years to build radio-controlled rockets which can be steered into such orbits beyond the limits of the atmosphere and left to broadcast scientific information back to Earth"

We must recall that this is long before any rockets were sent beyond the Earth's atmosphere and many years before the Russian success with Sputnik, the first artificial satellite, in 1957. In this same article, Clark also talks about the capabilities required of the launch rocket (about two-times the capability of the wartime V-2 rocket that bombarded London), the power requirement for broadcasting (~1.3 kW) and the availability of solar energy to power the satellite (using a solar concentrator and heat engine, but also suggesting developments in direct conversion via photo-electric devices) and finally mentioning the possibility of manned space-stations (necessary, perhaps, to change the vacuum tubes in the satellites).

Sir Arthur C. Clarke (1917-2008)

Unfortunately copyright Getty images - need a replacement!

Around this time, Clark started gaining success in writing science fiction. A series of novels emerged including "The City and the Stars", "Childhood's End", and "A Fall of Moondust", all now acknowledged as classics of the genre. In 1956, Clark relocated permanently to Sri Lanka (formerly Ceylon) to pursue his interest in scuba diving and undersea exploration and perhaps also to escape the UK's then draconian laws against homosexuality. In Sri Lanka he continued his productive writing on science fiction. In particular, in 1968, a collaboration with the American filmmaker, Stanley Kubrik, produced the novel and film "2001: A Space Odyssey"[3]. Despite a slow start and mixed reviews, the movie, gradually became the highest-grossing film of 1968 and gained a world-wide cult following. Today is widely regarded as one of the most influential films ever made. Although the name, Arthur C. Clarke, ultimately came to be associated much more with science-fiction books and movies and television series, Clarke always viewed his geostationary satellite proposal as his most significant contribution.

[3] https://en.wikipedia.org/wiki/2001:_A_Space_Odyssey_(film)

Clarke has three laws attributed to him: the first is a little mischievous, the second throws down a challenge, and the third, most highly cited, reflects his avowed atheism and the preoccupation in many of his novels of encounters with an advanced alien civilization.

1. When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.

2. The only way of discovering the limits of the possible is to venture a little way past them into the impossible.

3. Any sufficiently advanced technology is indistinguishable from magic.

Clarke was a “futurist”. In a 1976 interview, he predicted the concept of almost universal communication and access to knowledge using personal devices including a smart-watch. This was many years before the advent of the internet (~1990) or powerful search engines like Google (~1998) or smart-phones and smart-watches (~2000).

Sir Arthur C. Clarke passed away on the 19th March 2008 at the age of 90. He is buried in the central graveyard, Colombo, Sri Lanka, next to Leslie Ekanayake, his "only perfect friend of a lifetime".

The Clarke Orbit

An observer sitting on a satellite in the geostationary Clarke orbit would see the Earth suspended in front of them as a huge blue/white mottled sphere occupying about 17 degrees of arc (similar to a soccer ball at arm’s length). Looking to the left and right, our observer would see similar satellites clearly visible as bright stars. On the busy parts of the geostationary orbit, satellites can be packed at the minimum separation of just 74 km (0.1 degree of longitude) and ten or more might be visible on either side. The nearest ones would be similar in brightness to Sirius, the brightest star, and their ~25 meter wingspan could almost be discriminated by the naked eye (1 arc-minute resolution). A pair of binoculars would bring one clearly into focus. These satellites are large objects weighing several tons and sporting huge solar panels (wings) and large antenna arrays. With a good telescope, our observer would see an entire line of satellites, all in a very exact straight line, all equispaced by 0.05 degrees (the chord of circle subtends the same angle anywhere on the circumference), with gradually diminishing brightness, extending away into the distance on either side, and closing somewhere behind the Earth.

More than a few of the satellites are inactive, having run out of station-keeping fuel or having failed or simply become obsolete (new protocols require that such satellites now be moved out of the way to a higher 'graveyard' orbit). There is the famous example of the zombie satellite, Intelsat's two-ton Galaxy 15, which wandered along the Clarke orbit for most of 2010 happily transmitting (and interfering with its neighbors) while ignoring all guidance commands from the ground. The situation was only resolved fortuitously after the reaction wheels eventually reached maximum allowable rpm and the satellite lost the ability to correctly orient itself. The satellite slowly rotated until the solar panels pointed away from the Sun and, after a while, the batteries discharged to dead flat. When the solar panels finally rotated back to face the Sun, the battery started charging and the system automatically re-booted. As of 2017, Galaxy 15 is again under control and a fully functioning member of the satellite community.

The geostationary Clarke orbit is a popular place and interference in communications or even physical collisions are a real issue. The European Space Agency compiles a list of objects in or very close to geostationary orbit. As of 2016, it listed 1484 objects of which 471 are still actively controlled, 747 are drifting, 190 are caught in a libration orbit (explained below), and there are a few with incomplete data.

In theory, the Clarke orbit is unique and extremely precisely defined. The satellite has to orbit at exactly the same rate that the Earth revolves on its axis. The Earth revolves with respect to the fixed stars once in 23 hours, 56 minutes, and 4.0832 seconds. This is one sidereal day. The more familiar 24-hour solar day is about four minutes longer (= 24 hours x 1 day / 365 days) because each day the Earth advances roughly 1 degree in its orbit around the Sun. The satellite has to hold its position in the sky to much better than 0.1 degree otherwise it risks interfering with the neighboring satellites. It also has to hold this position for 10 to 20 years – a typical lifetime for a satellite. Simple calculations would suggest that the orbital radius needs to be exact to within a few millimeters! But, in reality, there are significant perturbations and the satellites have to be under active position control. Small orbital corrections are made about once a month. The satellites are allowed to drift several kilometers from their target locations.

There are several forces that can disturb a geostationary orbit. The largest of these are the familiar tidal forces caused by the gravitational fields of the Moon and Sun. The ellipsoidal equatorial bulge in the Earth and in its gravitational field is less of a factor here since the orbit has to be almost perfectly circular and lie almost exactly at the equator. However the Earth is not only fatter around the waist, it is also significantly "lumpy" and the corresponding lumpiness of its gravitational field has noticeable effects. In particular, it creates two stable points in the geosynchronous orbit towards which satellites are attracted. One is at longitude 75^{o} E in the middle of the Indian Ocean and the other is at 105 ^{o} W over the Eastern Pacific. Satellites are attracted towards these points, but with nothing to damp their motion, they oscillate slowly back and forth or "librate" around these positions with periods of several years (seen from the frame-of-reference of the Earth's daily rotation). These trajectories can be very complex sometimes incorporating both of the stable points and are also rendered chaotic by the added forces from the Sun and Moon. There are some analogies with the chaotic trajectories of many Lagrange objects (see Chapter +10 on Kepler).

As well as the effects of the gravitational fields from the Sun, Moon, and Earth itself, there are also smaller forces caused by solar pressure on the large solar cells and antennas. Altogether a satellite must be able to compensate about 4 m/s of velocity change (delta-V) per month of operation. This delta-V is accomplished with small chemical (e.g. hydrazine) thrusters or with ion-thrusters on the more recent satellites. Ion-thrusters operate using a strong electric field to accelerate heavy ions, typically Xenon, to very high velocities of 20-50 km/s. The thrust produced is tiny, but the rate of "fuel" consumption is even tinier – an important consideration if you're station-keeping for 10 to 20 years. The thrust divided by rate of fuel consumption is a key metric called specific impulse and for a rocket engine in a vacuum, this reduces simply to the effective exhaust velocity. Ion thrusters typically run with exhaust velocities a factor of ten higher than chemical rockets, so a given mass of fuel lasts ten times longer. The reason for this huge apparent advantage is that ion thrusters require significant amounts of electrical energy that has to be provided by the satellite's solar cells. This is in sharp contrast to chemical rockets where the fuel must simultaneously provide both the source of energy and the propellant material.

Geostationary Satellites

The multitude of satellites positioned in the geostationary Clarke orbit serves myriad functions and communities. Most of the satellites are dedicated to broadcasting television programming and are associated with the familiar rooftop dish antennas seen all over the world and especially in developing countries. The more recent satellites are also capable of uplink and downlink data services at moderate data-rates supporting internet access for their customers. Certain slots in the Clarke orbit are preferred for servicing large population centers. These slots are highly sought after and disputes often arise between nations at similar longitudes. The International Telecommunication Union (ITU), a part of the United Nations, is responsible for allocating positional slots and frequencies for the Clarke orbit.

Intelsat's Galaxy-15
geostationary satellite

The satellite is in 'folded' configuration prior to launch but clearly illustrates the scale of these devices. The satellite weighed roughly two tonnes at launch.

It was launched from Kourou, French Guiana in October 2005 on an Ariane heavy-lift rocket.

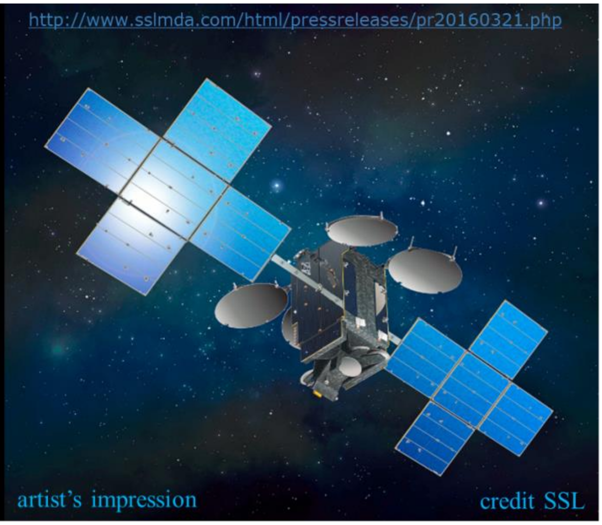
This satellite was destined to is become the infamous 'zombie' satellite. The operators did recover control. It is currently positioned at 133 deg. W.

One big change over the years has been the reduction in the size (and cost) of the customer's dish antenna. The early smaller satellites, had limited transmitter power and had much smaller antennas operating at lower frequencies (longer wavelengths) with correspondingly much less directionality or gain (see the later section on Syncom 3). This meant that only very large radio telescopes, ten or more meters in diameter, could be used to receive signals from the satellite. As the payload capabilities of launch vehicles improved and as technology of the satellites progressed, the required dish size for the customer has shrunk dramatically. In the 1980's a 3-meter (10 foot) dish was common. These would often be on an equatorial mount, so that the dish could move on an arc to point at any of several satellites. At that time, many of the satellites were transferring television programming material from one location to another for local terrestrial re-broadcast. This material was in analog format (NTSC or

PAL) and unencrypted, so a wide variety of free material was available for consumers.

Unfortunately, that situation quickly changed. Almost all program material now is encrypted digital video and is inaccessible without paying subscription fees. On the positive side, however, a single satellite can provide hundreds of television channels and can be accessed with tiny fixed dish of about 500 mm (20 inch) diameter. The beam-width at a typical 12 GHz (25 mm or 1-inch wavelength) is roughly 25/500 radians or about 3 degrees. This allows for the antenna to be pointed relatively easily. It does also mean that the antenna may see signals from more than one satellite. The ITU ensures that closely-spaced satellites are allocated different frequency bands and polarizations so they can be discriminated at the receiver.

EUTELSAT 7C
Geostationary satellite
from Space Systems Loral (SSL), Palo Alto, California
The satellite is 'all-electric' (only ion-thrusters), and will offer 44 independent transponders with steerable spot beams. It is to be launched in 2018 and positioned at longitude 7 degrees east servicing principally the middle east and Africa.



Modern geostationary satellites are huge intricate machines weighing several tonnes[4]. They are about the size of a small school bus when neatly folded and packed to fit into the launch vehicle's payload faring. Upon reaching an initial staging point in low-Earth orbit, the satellite emerges and cleverly unfolds itself origami-like to reveal the large antennas and giant solar-array wings - like some gargantuan butterfly emerging. After the system has been thoroughly tested, the satellite must be moved to geostationary orbit and to its final position in that orbit. This can be accomplished with chemical rockets where a first burn puts the satellite

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[4] https://www.mwrf.com/systems/satellites-provide-distant-connections
http://www.sslmda.com/html/pressreleases/pr20160321.php

into a highly elliptical transfer orbit with an apogee (maximum distance from Earth) roughly at geosynchronous radius. When the satellite is at its apogee, a second burn is done to circularize the orbit and make it geosynchronous. A third major burn is required when the satellite crosses the equatorial plane to bring the orbit's inclination down to zero and make it exactly geostationary so that the satellite hovers at a fixed point above the equator.

The description above over-simplifies the process and ignores all the fine-corrections that must be done along the way. It also omits the final step which is to carefully coax the satellite into the exact desired longitude. Recent satellites have used ion-beam thrusters to slowly accomplish the entire operation over a period of many months. What may be lost in time-to-revenue may be more than made up for by capabilities that can be added (e.g. more fuel for longer station-keeping) when the heavy chemical rocket motor and propellants are eliminated.

The four key functional systems of these satellites are communications, power, engines, and control:

Communications: The job of the satellite is to provide communications to and from the Earth. For this purpose, there are large antennas for receiving and sending signals, there are low-noise amplifiers for receiving very weak signals from Earth, and there are high-power amplifiers for transmitting back to Earth. Generally, the satellite acts as a transponder or repeater. In some cases, this is simply as a "bent-pipe" where the incoming analog signal is frequency-shifted (to avoid interference between incoming and outgoing signals) and then greatly amplified for re-transmission and broadcast to Earth. In other cases, the signals are received and demodulated to digital form before being re-modulated onto a carrier and re-transmitted. In this latter case, any errors caused by noise on the weak uplink signal can potentially be corrected so that the clean data can be transmitted on the downlink. Reliability of all the components is a key issue since there is no possibility of repair (no manned missions other than Apollo have ventured this far from Earth). So there are duplicate or triplicates of many items and provision for switching signals through various paths to avoid failed components.

In particular, for the highest power levels, the final amplifier is typically a travelling-wave vacuum tube with a glowing red-hot cathode (and with the propensity for failure noted by A. C. Clarke). The travelling wave tube (TWT, usually pronounced 'twit') is a very wide bandwidth microwave amplifier that operates rather differently to a conventional vacuum tube with a control grid. In a TWT, the electrons ‘boiled’ off the cathode are formed into a beam (‘electron gun’) that makes its way down the center of a long wire helix. The design is such that the electron velocity closely matches the electromagnetic propagation velocity in the wire helix. As a result, there is a strong interaction with the electrons being velocity modulated by the fields from the helix and the helix picking up energy from the resulting bunching of electrons. A small signal inserted at the beginning of the helix can become a very large signal that can be picked up at the end of the helix near a return electrode. TWTs can provide large amplification factors and achieve microwave output powers of a kilowatt or more with efficiencies around 50% and lifetimes exceeding 10 years.

Power: These satellites include very large solar arrays with many square meters of active surface area capable of delivering several kW of power. The sizing must account for the fact that the solar cells degrade a few percent per year from exposure to UV-light and ionizing radiation in the space environment. The solar arrays are kept pointing directly towards the Sun, but the Sun is not always available. Twice a year around the spring and autumn equinoxes, the Sun lies near the equatorial plane. As a result, there is a period of 44 days twice a year when the Earth eclipses the Sun for a least a few minutes each day. At its maximum, the eclipse will last for 69 minutes and the satellite will be in total darkness for that time. The batteries must have sufficient reserve during that period to not only provide the electric power to keep the communications and control systems working but must also provide power to electrical heaters to maintain temperate on certain critical components (including the batteries themselves).

Engines: Even after the correct geostationary orbit has been reached, the satellite must be able to accurately maintain its position and orientation in space in the face of various disturbances. Also it is not infrequent for a satellite to be moved to a different orbital slot. And finally of course there is the issue of disposal (placement into a graveyard orbit). All these maneuvers require engines of some description. These may be small chemical rocket thrusters or simply compressed gas thrusters or the ion thrusters mentioned earlier. In all cases, there must be enough on-board fuel or propellant to last the 10 to 20 year lifetime of the satellite. Orientation or attitude can be largely handled by reaction wheels (as mentioned in the chapter on Kepler). But with any sustained disturbing torque on the satellite, the reaction wheels will gradually spin up to their maximum rpm and the thrusters will have to fire to absorb the accumulated angular momentum. Generally the solar wings are oriented north-south on their long axis and fixed pointing to the Sun (i.e. de-spun with respect to the satellite itself). In absolute terms, the spacecraft body and the antenna arrays are rotating uniformly at one revolution per sidereal day, so that the antennas always point down at the Earth. The solar panels rotate once per year to keep pointing at the Sun.

Control: Such a large complex multifunctional satellite obvious requires a powerful, extremely-reliable control system. This involves radiation-hardened computers with multiple-redundancies and with extremely robust low-data rate links to the ground for control commands and telemetry. In a worst-case scenario, the satellite should be able to reboot and automatically orient its solar panels towards the Sun and its low bandwidth antennas towards the Earth. The system reboot must be done from an extremely reliable non-volatile memory. There is no tape-recorder and no hard-disk drive on these satellites and ferrite core memory is a thing of the past. The system reboot is done from a small section of computer memory implemented in radiation-hardened electrically-erasable programmable read-only memory (EEPROM). EEPROM is similar in its basic operation to Flash-Memory (discussed in the chapter on Curiosity) but with word level addressability and with much greater reliability. These 'space-worthy' memories are deliberately designed in 'older' technologies with large feature-size (1 μm line-width) and typically claim perfect data retention over decades of time and over a wide range of temperature and voltage abuse and up to hundreds of krads of radiation (1 krad is more than enough to kill a human being). The Clarke orbit is actually inside the outer edge of the upper Van Allen radiation belt. The radiation in the upper belt is mainly high-energy electrons (beta-radiation) against which the aluminum structure of the spacecraft can be quite effective. A sandwich of Aluminum/Tantalum/Aluminum is found to be especially effective weight for weight.

Syncom 3

Syncom 3, launched in 1964, was the very first satellite placed in the Clarke orbit and was the first to realize Clarke's vision of globe-spanning communication from geostationary orbit. It is the oldest of the spacecraft that we will talk about. It was very tiny and crude compared with today's behemoths and it is also very dead, but it still holds huge historical significance.

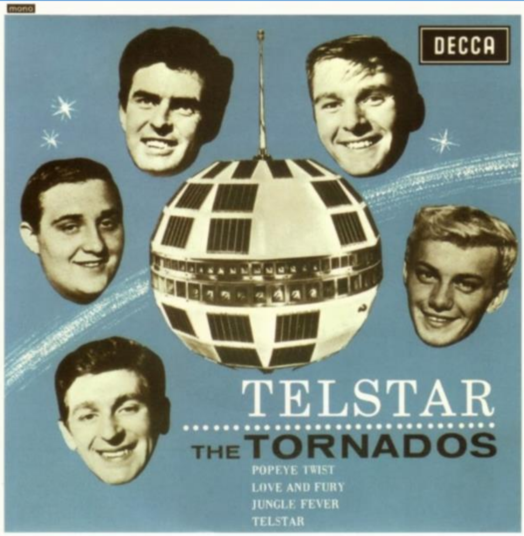
The "space-race" between the US and USSR started with "Sputnik" in 1957. Sputnik was the first man-made satellite of the Earth. It was launched in low Earth orbit on a modified ballistic missile and did nothing but transmit 'beep-beep' tones at 20 and 40 MHz.for three weeks until the batteries failed. But the American public was shocked. With this success, the general perception of the USSR as a technologically backward nation disappeared overnight. Eighty days later, the US launched its response, Explorer 1 and the space-race was on! It would culminate eleven and a half years later with the Apollo-11 lunar landing on July 20, 1969 (see previous chapter).

"**Telstar**", an instrumental by the Tornadoes, a British pop group, topped the charts on both sides of the Atlantic.

The three-minutes of music were released on the Decca label in August 1962, just a few weeks after the launch of the Telstar satellite.

The recording was distributed as a 'single', meaning that the music was pressed into 7-inch diameter vinyl phonograph disks, also called "records".

https://www.stereogum.com/1995099/the-number-ones-the-tornados-telstar/franchises/the-number-ones/



The first communication satellite, Echo-1, was launched in low Earth orbit in 1960. It was a 100-foot (~30 meters) metallized plastic balloon - very clearly visible at dawn or dusk as a magnitude 0 object passing rapidly overhead. Its operation was entirely passive. By aiming signals at it from one large dish and listening to the feeble radio reflections using another large disk, one could transmit between any two stations from which the satellite was temporarily visible. Two years later, in 1962, the first active communications satellite, Telstar 1, was launched with a real 4 GHz 2-Watt TWT active transponder. All these early satellites were in low-Earth orbit and required both the transmitting and receiving dishes to pan rapidly across the sky as the satellite passed overhead. A transatlantic link could be maintained for about 20 minutes. The excitement over this achievement is perhaps best reflected in the famous instrumental "Telstar" by the Tornadoes[5], an English pop group. That year the song reached number one

[5] https://www.express.co.uk/expressyourself/331340/The-satellite-that-launched-the-sixties

on the charts both sides of the Atlantic – rare for an instrumental-only track and a prelude to the 60's British invasion by the Beatles and others.

The Olympic Games were due to be held in Tokyo, Japan, in October 1964. As a demonstration of modern technology, what better than to be able to transmit live television signals to the American public? This is in the days when television signals could be broadcast successfully across the continent via terrestrial microwave links, but there were very few trans-oceanic cables. The cables that existed had bandwidths of only 1 MHz or less and were dedicated to frequency-division multiplexed telephone or teletype and could not support a television signal. So, with both the Japan and US governments on board, and after some experiments to prove feasibility, a new satellite, Syncom 3, was prepared and launched on 16 August 1964. Through a series of burns, it was moved into a rough geostationary orbit and after further testing it was moved gradually into its final position over the mid-Pacific around the date-line at 180 degrees longitude (and zero latitude, of course). These maneuvers were completed just in time. On October 10th, eager American viewers were able to view the opening ceremonies of the 1964 Summer Olympic Games live in their living rooms - the first live color television transmission from overseas to the US!

The opening ceremonies, however, were about all that viewers in the US did see. Both NBC and CBC had signed up at $150 per minute of programming, but NBC's lawyers wanted exclusivity and had issues with NASA's open access policy. In the end only CBC viewers watching in

Canada got the full benefit of live coverage of the sporting events. American viewers had to wait for the (much higher quality) photographic film of the events to arrive by airplane the following day.

The Clarke geosynchronous orbit is a very long way away and huge antennas were still required at both ends of the trans-Pacific link (Tokyo, Japan, and Point Mugu on the California coast), but at least the antenna pointing was fixed which meant a huge simplification in the design and operation of the ground antennas. The satellite, Syncom-3, was a small cylinder 71 cm diameter and 39 cm high (28 inches diameter x 15 inches high) weighing 39.0 kg (86 pounds) unfueled[6] The satellite was spin-stabilized in alignment with Earth's north-south axis so the antenna radiation patterns had to be circularly symmetric about the same axis. This requirement limited the antenna gains. Three collinear slotted dipoles gave about 6 dB gain for the 1.8 GHz downlink (the radiation pattern was pancake-shaped with about 25 degrees 'thickness'). On top of the transmit antenna was a simple dipole (2 dB gain) for the 7.4 GHz up-link. The outside of the drum was covered with solar cells providing 28 Watts to power the electronics including the dual 2-Watt TWTs. Nickle-cadmium rechargeable batteries powered the spacecraft for the short intervals that the spacecraft flew through the Earth's shadow. Much of the inside of the cylinder was devoted to the apogee rocket motor that circularized the initially highly elliptic orbit. Simultaneous bi-directional operation (duplex) was possible for multiple telephone conversations. But, in particular, one of the two transponder channels supported 13 MHz of bandwidth (more than sufficient to allow one color television signal to be relayed from Tokyo to California).

Syncom 3 was launched in 1962 and, like all spacecraft, incorporated technology that had been proven through the passage of time to be robust and reliable. For Syncom 3, this means late 1950's technology, in other words, a lot of discrete components (resistors, capacitors, and inductors and diodes and transistors sparingly) and electromechanical relays (see next section). Transistors had barely been invented and could only operate up to a few tens of MHz but were already favored over vacuum tubes because of the low power consumption. Only specialized vacuum tubes such as TWTs, Klystrons, and Magnetrons (as found in your microwave

[6] https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1964-047A
https://space.skyrocket.de/doc_sdat/syncom-1.htm
http://www.boeing.com/defense-space/space/bss/factsheets/376/syncom/syncom.html

oven) could operate in the GHz region. Syncom-3 received uplink signals at 7.363 GHz (4.1 cm) and re-transmitted them to Earth from the TWTs at 1.815 GHz (16.5 cm). The incoming 7.363 GHz signal was immediately down-converted by a passive nonlinear diode to 34 MHz intermediate frequency so it could be amplified by a 16-transistor amplifier[7]. After amplification it was up-converted to 1.815 GHz for further amplification by the TWT and thence to the downlink antenna. The system was entirely analog and employed frequency modulation. A particular issue was how create the sinusoidal ~7 GHz tone required to down-convert the incoming signal. The solution was to start with a strong vacuum-tube quartz-crystal oscillator at 28.8917 MHz and put the resulting sinusoidal voltage through a remarkable eight stages of frequency-doubling (a factor of 256) to get up to the GHz range to be mixed with the incoming signal. All but the first of the eight stages were accomplished with a passive varactor diode doubler circuit (full wave rectifier) with a tuned ‘tank’ or flywheel LC circuit or cavity carefully tuned to minimize loss in each successive stage.

Satellite commands and telemetry were transmitted over VHF at 148 and 136 MHz, respectively, using four ¼-wave whip antennas evenly spaced around the bottom end of the satellite. Commands were sent in the form of a sequence of pulses, the number of pulses indicating the desired command. The commands were thus stored in transistor counter circuits incremented by the incoming pulses. A large number of mechanical relays and electrically-controlled valves were employed to translate from the satellite commands into functions such as the switching power between amplifiers or the firing the attitude control jets.

Syncom 3 was kept in service until 1969 when its station-keeping fuel ran out. Since that time it has been uncontrolled and is very slowly drifting westward along the Clarke orbit at a few tenths of a degree per day slower than the Earth’s rotation. Its future is unclear, but the atmospheric and tidal drag at the Clark orbit is insignificant and all the other perturbations tend to be periodic (averaging to zero). So Syncom 3 and its brethren will likely be found in the vicinity of Earth’s Clarke orbit for many millions if not billions of years – presumably long after the human race has disappeared - interesting artifacts for future alien explorers to come upon.

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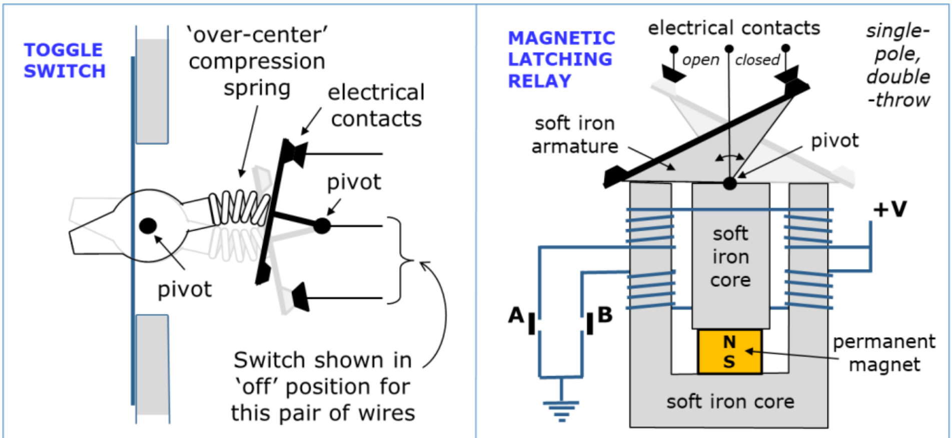
[7] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19670015715.pdf
http://www.hughesscgheritage.com/the-syncom-iii-mission-and-spacecraft/
D. Martin, P. Anderson, L. Bartamian, “Communication Satellites”, 5th ed. , The Aerospace Press, El Segundo, California.

Electromechanical memory

Syncom 3 had a very simple control structure enabling it to respond to simple telemetry commands to turn thrusters on or off and to switch different amplifiers in and out. This involved electromechanical relays and it is likely that latching relays were used. Latching relays represent about the earliest form of electrically programmable memory. Latching relays come in two forms: to use modern parlance, they can be either volatile (requiring a continuous source of power) or non-volatile (remembers even when the power is turned off).

Electrical relays represent a very old technology. In 1820, the Danish Physicist, Hans Christian Oersted, discovered that electrical currents produce magnetic fields and by 1835, the American scientist, Joseph Henry, had created devices like the electric doorbell and the electromagnetic relay. The name ‘relay’ came from its early adoption as a repeater or ‘relay’ in telegraph systems. The small Morse-code on/off (binary) signaling arriving at the end of a long copper wire could be applied to a magnetic coil or solenoid to cause movement in a lightly-sprung switch that repeated the incoming signal but at much higher voltage and current ready to be fed into the next length of wire. The relay is a binary amplifying device that long preceded vacuum tubes (1904) and transistors (1947). It was the mainstay of early electric calculators and computers and was ubiquitous throughout the 20th century as a switching device on the electric power grid and especially in automotive applications. Even to this day, turning the ignition key in your car probably takes you through two stages of electrical amplification by relay from a few hundred milliamps current at the contacts on the ignition key to several Amps after the first relay. This current then drives the final relay, the starter-solenoid, that switches on the one roughly hundred Amps (1 kW) that the electric starter-motor requires to turn the car engine over. The advantages of relays in automotive applications include their robustness to extremes of temperature and voltage and even to physical shock and vibration. The disadvantage, of course, is switching speed and, in some cases, cost.

Memory involves two or more stable states. The states are energy minima and between them must be an energy barrier sufficient to prevent any inadvertent changes of state. The energy may be associated with the mechanical configuration or the magnetic or electric system. A familiar example is the everyday electric light switch that we click on or off (toggle) without even thinking. The spring is least compressed (lowest energy) in either the up or down position and has highest energy half way in between when the spring is most compressed. The difference between the highest energy and the lowest energy is the *energy barrier* that must be overcome (see tutorial box at end of chapter). Roughly, this is the force that your finger must apply to the switch times the distance to the midpoint.



Manual binary mechanical memory element (electric light switch or toggle switch)

Electrically actuated latching relay with a permanent magnet and separate windings

Of course, the human finger can be replaced by a electromechanical actuator creating a latching relay. However there are also forms of latching relay that are entirely magnetic relying either on magnetic hysteresis or switching between stable magnetic configurations. The diagram illustrates a latching relay incorporating a permanent magnet that ensures the two distinct energy minima. Switching from one state to another is accomplished by momentarily pressing button A or B. The coils in paths A and B are wound in opposite directions. Current passing through path A reinforces the field in the left half yoke (core) and reduces the field in the right half yoke. Conversely, current passing through path B reinforces the field in the right half yoke and reduces it in the left. The armature flips towards whichever half-yoke has the highest field and carries the most flux. The intermediate state with the armature not completing either magnetic circuit has higher energy and is unstable. Strictly, the dual oppositely-wound coils are not necessary since simply reversing the current would accomplish the same function. But this was often a feature of early devices like this where the complexity of the electromagnetic device was increased slightly in order to make the external circuits easier to implement.

The devices shown above have two states (binary) and implement what is called a single-pole, double-throw (SPDT) switch meaning a single wire can be connected to either of two other wires. Switches and relays can implement remarkably complex functions. The ultimate might be the Strowger switch. Not a lot is known about Almon Brown Strowger[8], but his 1891 patent has his address as Kansas City. The story goes that he had an undertaking business (funeral parlor) and gradually became suspicious that the local telephone operator was deliberately directing his customers' calls to a competitor (at that time, the connection was made manually in response to verbal requests). The telephone operator happened to be the wife of a rival funeral director. For whatever reason, Almon Strowger set about, with some help from family members, to create an automated telephone switch and thus eliminate the human operator.

The Strowger switch[9] in its later manifestations was a remarkable 2-pole or 3-pole 100-throw electromechanical switch. Thousands and thousands of these switches filled giant telephone exchanges and supported the worldwide switched telephone network through much of the 20th-century. The actuation was by magnetic solenoids but the memory mechanism was purely a mechanical ratcheting mechanism. The storage capacity was 1 selection out of 100 or $\log_2(100) = 6.64$ bits. Or, since the same mechanism could be used to detect whether a line was busy (engaged) or not (i.e. 1-bit), one could argue that the mechanism was capable of storing 100 bits as a read-only memory (ROM).

[8] http://kshs.org/kansapedia/almon-strowger/16911 Kansas Historical Society

[9] https://en.wikipedia.org/wiki/Strowger_switch

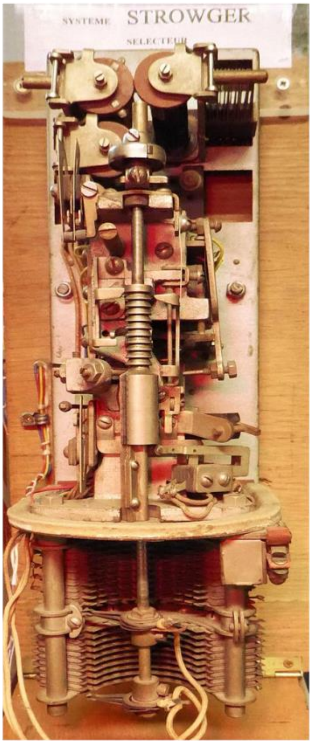
The famous Strowger switch patented in 1891 was invented by Almon Brown Strowger, an American undertaker and inventor.

This switch quickly replaced the many manual telephone exchanges and operators. Automatic exchanges with many thousands of such switches supported the public telephone network worldwide for much of the 20th century.

This device shown is a 2-pole 100-way switch. The switching motion was achieved in 10 vertical steps then 10 rotary steps in synchronous correspondence with two consecutive digits dialed on a rotary phone. Electromagnets provide the stepping motion. No power is required to maintain the switch position (this is a non-volatile memory)

Courtesy of Pierre Andre Leclercq and the Regional Museum of Telecommunications in Flanders, France

https://en.wikipedia.org/wiki/Strowger_switch#/media/File:T%C3%A9l%C3%A9graphie,_Systeme_Strowger.jpg



The rotary dial is long gone except in antique stores and old movies. In operation, the human finger was placed on desired number and the dial was rotated clockwise to the finger stop. When released, the dial rotated back to its resting position limited by a mechanical governor to 45 rpm. As it rotated back, and a pair of contacts opened and closed ten-times per second counting out the number selected. Every time the contacts closed, current flowed from the 48-volt battery in the exchange through the copper pair to the home and via the Strowger switch in the exchange. Each pulse advanced the ratchet and the pair of contacts by one step until the desired number was reached. The quarter-second pause while the customer dialed the next number signaled that the selection was complete and the signals should go to the next switching layer. Each Strowger switch actually handled two successive digits – the first with 1 to 10 steps along the axis and the second with 1 to 10 steps of rotation. In this manner, connections involving many successive digits could be handled completely automatically. The switch was non-volatile in that the selected connection was maintained even if an intermediate exchange lost power. Starting in the 1960s, Strowger switchgear was gradually replaced with push-button two-tone signaling and electronic (transistorized) switching at the exchange.

As we descend from the Clarke geosynchronous orbit at an altitude of 35,786 km (22,236 miles), we find the outer Van Allen belts becoming gradually stronger. The outer belt is mainly high-energy electrons against which radiation shielding can be quite effective. The navigation satellites like GPS and Glonass and others are able to operate in this region[10]. They have relatively high inclination orbits to give coverage at high latitudes. A large number of satellites are deployed (referred to as a constellation). These satellites are widely and evenly spaced around the Earth so that a receiver on the surface of the earth has a high chance of having line-of-sight to at least the minimum four satellites[11]. The GPS satellites operate with an orbital period of exactly one-half a sidereal day (11 hours 58 minutes) with the result that the satellites advantageously pass over the same ground-track each day.

As we move inward closer to Earth, the radiation levels drop to a minimum and then increase again as the inner Van Allen belt is entered. The inner belt has higher levels of radiation and is dominated by very high-energy protons (100 MeV) rather than electrons. At about 1000 km (600 miles) the radiation drops again as Earth's tenuous atmosphere starts to have an effect. Most of the satellites in Low Earth Orbit (LEO) are below this altitude. The Iridium constellation of communications satellites is positioned at 781 km altitude (485 miles). The Hubble Space Telescope is at 595 km (370 miles). The International Space Station (ISS) is at 340 km (211 miles). At this altitude, drag from the Earth's atmosphere is starting to become significant. The ISS needs an altitude boost of a few kilometers every month or so[12]. Below this altitude, atmospheric drag quickly becomes a dominating factor. Large low-mass objects spiral inward to a fiery death within a few days. Compact heavy objects at

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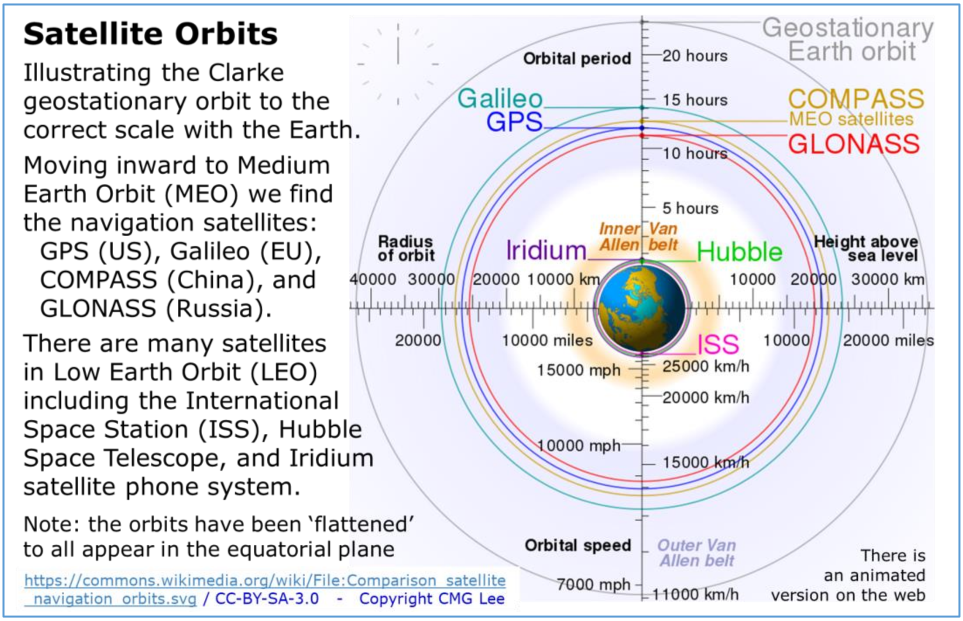
[10] https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg

[11] Four satellites are required if there is no local time reference available at the receiver.

[12] https://space.stackexchange.com/questions/9087/how-often-does-iss-require-re-boosting-to-higher-orbit

similar altitude may take many months before finally succumbing and adding their remains back to Mother Earth - which brings us to the next chapter.



The obvious subject for the next chapter (scale = 10,000,000 meters or 10,000 km) is our home planet, Earth, and all that it contains. Earth has a mean diameter of 12,742 km (7918 miles). A huge drawback of using the Clarke orbit for communications is the propagation delay. This is not a problem for broadcast transmissions, but it is very much a problem for real-time human or machine interaction. It takes about an eighth of a second to travel from Earth to the satellite or vice-versa. A round trip for two individuals on the Earth has four such legs, totaling half a second delay before any response can be heard from the other end. This makes human conversation awkward and unnatural and is prohibitive for many automated applications. The next chapter will talk mainly about the modern terrestrial international communications network (Internet) and the massive amounts of data-storage that support the world-wide web – such was Arthur C. Clarke's vision from 50 years ago.

Further Reading

Interview with A.C. Clarke in 1976. http://www.networkworld.com/article/2879652/internet-of-things/watch-arthur-c-clarke-predict-smart-watches-the-internet-and-cell-phones-in-1976.html

T. Flohrer, S. Frey "Classification of Geosynchronous Objects, Issue 18", European Space Agency, ref. GEN-DB0LOG-00195-OPS-GR, 3 June 2016. https://www.dropbox.com/s/u418iblbfk7w0ew/ESAclassification_issue18_.pdf?dl=0

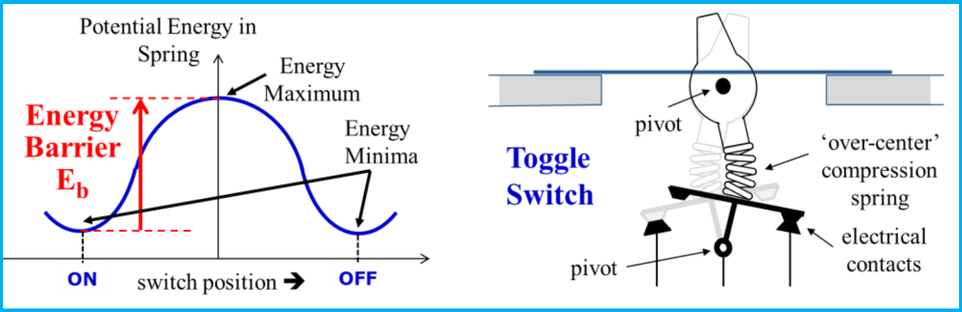
"Syncom Engineering Report, Volume II", NASA Technical Report R-252, Goddard Space Flight Center, April 1967 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19670015715.pdf

http://www.satobs.org/geosats.html

John Slater, Western Carolina University, "A Technological Triumph? The 1964 Tokyo Olympic Games and Television Coverage in North America", http://library.la84.org/SportsLibrary/NASSH_Proceedings/NP2000/NP2000zzb.pdf

"The World's First Geosynchronous Communications Satellite" https://web.archive.org/web/20101111082736/http://www.boeing.com/defense-space/space/bss/factsheets/376/syncom/syncom.html

Energy Barrier



The concept of an energy barrier is important in memory and data-storage. It can be illustrated using a simple toggle switch with two stable positions (detents) corresponding to energy minima. Given a small disturbance from these positions, the switch will automatically return to its original position. It takes a large deliberate force to move the switch up and over the energy maximum from one position to the other. The presence of an *energy barrier* separating stable states is essential for any memory mechanism. The barrier should be sizable so that small vibrations or just a fly settling on the switch should not cause it to flip.

There is a strict fundamental limit on how small one can make a mechanical switch or indeed any memory system. The energy in a system scales as the cube of the linear dimension. Eventually one could make a switch so tiny that even a fly could disturb it. Making the switch even smaller, one even has to worry about air-molecules buffeting the switch (Brownian motion). The switch will jiggle around randomly in its detent and not be at the bottom of the energy minimum but will have an average additional energy given by ½kT, where T is the absolute temperature and $k = 1.38\times10^{-23}$ Joules/Kelvin is Boltzmann's constant. The probability that a random fluctuation in thermal energy will exceed the energy barrier and cause a device to spontaneously switch is given by the

Arrhenius equation: **Probability = $f_0 \times \delta t \times \exp(-E_b/kT)$**

where f_0 is a prefactor called the attempt rate (e.g. related to how often air molecules hit the switch) and δt is a short time interval of interest. Because of the exponential function, there tends to be a fairly sharp threshold in scale or E_b below which thermal effects become important. This equation applies equally to mechanical and electrical systems.