Introduction to Artificial Satellites

The world's first artificial satellite called Sputnik I was launched successfully on October 4, 1957 by the U.S.S.R (Russia now). It looked like a basketball and weighed only 183 pounds (see figure 1). It was orbiting elliptically around the earth and took about 98 minutes for a complete cycle [1]. After the successful launched of Sputnik I, Russia has become the first space power. Of course, their competitor US would not allow lagging behind U.S.S.R. The response from US was Explorer I. On 31 January 1958, Explorer I lifted off from the Cape Canaveral, Florida. It looked like a jet engine(see figure2) and a cosmic ray detector designed to measure the radiation environment in Earth orbit, verified the that the existence of Van Allen Radiation Belts was due to the charged particles trapped in space by Earth's magnetic field [1,2].

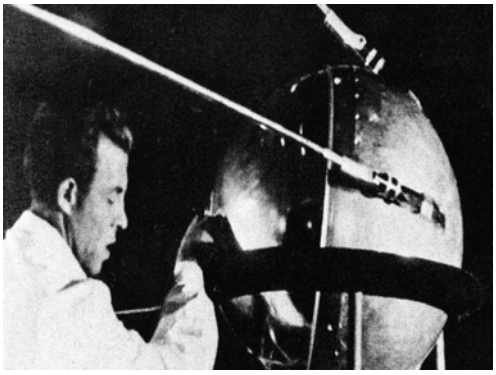

Figure 1: SputnikI
Image credit: NASA/ Asif A. Siddiqi
http://www.nasa.gov/multimedia/imagegallery/image_feature_924.html Accessed: 25 February 2008

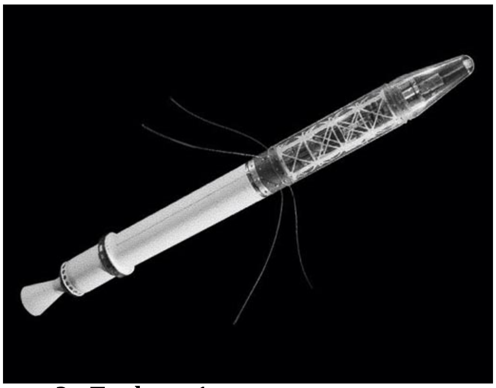

Figure 2: Explorer 1
Image credit: NASA
http://www.jpl.nasa.gov/explorer/captions/explorer-1.php Accessed: 25 February 2008

The success of Explorer I demonstrated the potential of artificial satellites and lead to a rapid development of its applications. Nowadays, artificial satellites applications are not only used for scientific measurements like solar activities, observation of universe, earth science, but also for improving our daily life, such as global positioning system(GPS), weather forecast, satellite TV, telecommunication, etc . In this essay, I will firstly talk about the satellite orbits, and then I will focus on two main orbits (geostationary and polar orbit) to discuss their features and applications. Secondly, I will talk about the principle of weather forecast and GPS by using satellites. Finally, I will give a brief summary.

Satellite orbits

Many scientists had done many observations in the outer space and tried to find the laws governing planetary motion. In the late 16th century, Kepler analyzed the data, which were obtained from Tycho Brahe regarding the positions of the planets, and summarized them to be Kepler's laws [3]. Kepler's 1st law states that the orbits of the planets around the Sun are ellipses and the Sun to be one of the foci. After that Isaac Newton used his Newton 2nd law, Newton law of gravitation and calculus to explain the Kepler's laws in a more fundamental way to describe planetary motion. The calculation shown that, the orbit of planetary motion should be either elliptical, parabola or hyperbola. This result can also be applied to the earth instead of the sun to explain the artificial satellites motion. If we plot a graph of the energy distribution from the result of Newton's laws (see figure 3b)(proof omitted), we can get a local minimum which corresponds to a circular orbit. When the total energy E lower than E_o, the orbit will be an elliptical orbit(oscillation back and forth with a finite radial velocity) like a ball rolling back and forth on a bowl. Otherwise, it will be a parabola ($E=E_o$) or hyperbola ($E>E_o$) (for the case of $E \geq E_o$, satellites would not return back) [4].

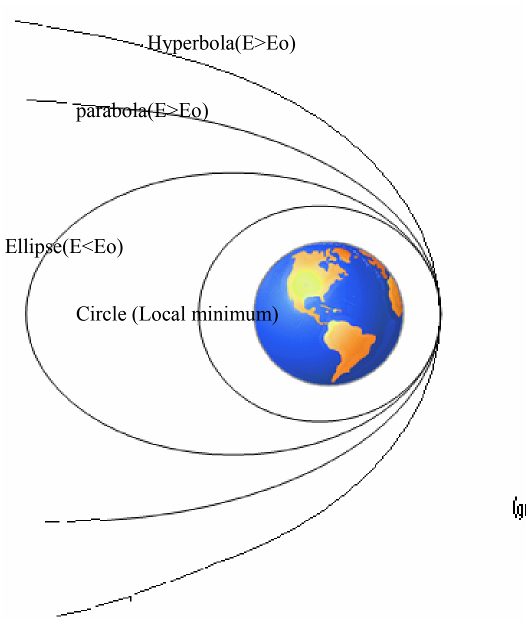

Figure 3a: The orbits of various energies

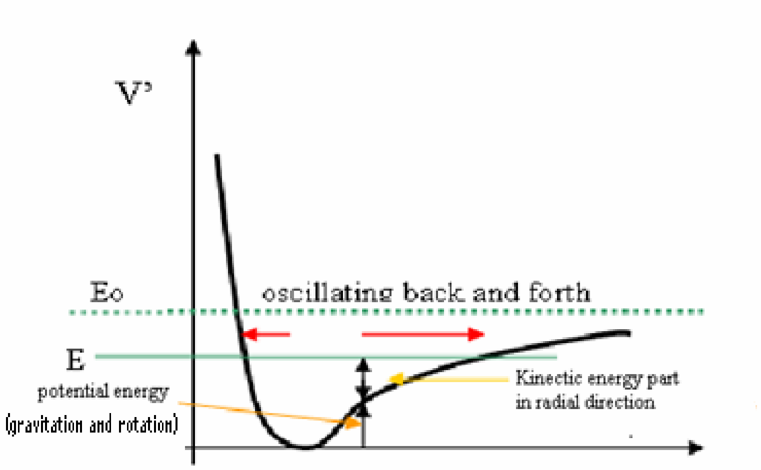

Figure 3b: Dynamic in the potential wall with a fixed energy E

Geostationary Orbits

For a geostationary satellite (GS), as the name implied, it is fixed over the sky from the rotating earth's frame point of view. How to get the height of the geostationary satellite? By using a simple relation $G\frac{mM}{r^2}=\frac{mV^2}{r}$ with $V=\omega r$ (gravitational force balances the centrifugal force) (G is the gravitational constant, m and M are masses of the satellite and the earth, V and ω are the velocity the angular velocity of the satellite, and r is the separation of between the satellite and the earth) for circular motion and rearranging them, we get $r=(\frac{GM}{\omega^2})^{1/3}=(\frac{T^2GM}{4\pi^2})^{1/3}$. Substitute the angular velocity synchronized with the earth's rotating period (T=23 hrs, 56 mins, 4.09 secs) to the above equation, we get r~42,164km. Subtracting it with the Earth's equatorial radius, 6,378 km, gives the altitude of ~35,790 km[5]. This is the condition to fix the satellite over the sky without falling. Geostationary orbits only valid at the circular ring above the equator (see figure 4). So you may ask a natural question: why GSs are still being used world-wide? Let us consider a counter example: If we are using a moving satellite for satellite TV, we need to move the satellite dish toward the satellite continuously to get the signal, why not choose a geostationary satellite? Therefore GSs can transmit signal continuously to a stationary point. This advantage helps us do a continuous observation in meteorology like tracing the movement and development of typhoon. Therefore, GSs are widely used for weather forecasting, satellite TV, satellite radio and most other types of global communications. Obviously, GSs has a poor resolution near two poles.

Polar Orbits

Unlike the Geostationary satellite, Polar-orbiting satellite(POS) can cover the polar region with a high data-collection resolution. POSs orbit at polar inclination (moving direction relative to earth is from N-S)(see figure 4). The main feature of POSs is that these satellites operate in a sun-synchronous orbit, that means POSs would pass the same place overhead several times at regular time intervals. For example, a satellite could pass over the same spot at 4pm, 10pm, 4am, and 10am every day. This feature enables us to collect the data at a consistent time for long term comparisons such as climate change.
By the incorporation of the Geostationary and Polar-Orbiting satellites, the world Meteorological organization forms a Global Observing System (GOS)(See figure 5), which collects the outer space and the earth observations data of the atmosphere and ocean surface stage for the preparation of weather analyses, forecasts, advisories and warnings[6].

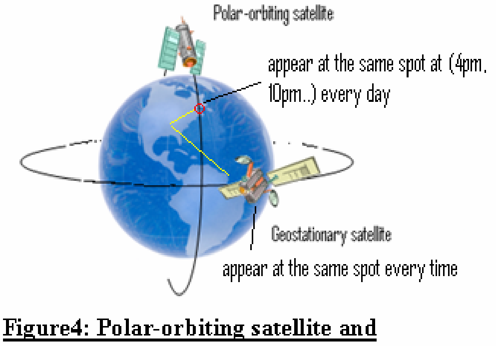

Figure4: Polar-orbiting satellite and geostationary satellite

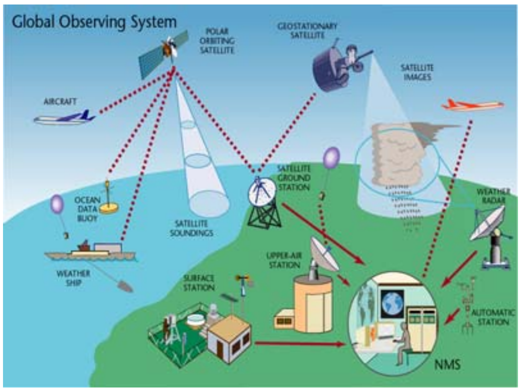

Figure 5: Global Observing System (GOS)
Image credit: World Meteorological Organization
http://www.wmo.ch/pages/prog/www/OSY/GOS.html
Accessed: 25 February 2008

Global Positioning System (GPS)

Contrary to popular belief, GPS does not employ geostationary satellites. GPS consists of 24 satellites, each of them possesses an orbital period about 12 hours and have a total of six orbital planes(The six planes have nearly 55° inclination and are separated by 60° right ascension of the ascending node[7,8]) (see figure 6). Under this network configuration, at least 4 satellites are always detectable from any point on the Earth at any time[8]. Each satellite carries accurate atomic clock with a high accuracy (~1 nanosecond) to measure the proper time in the satellites. The operation of position determination is as follows: Each GPS satellite is transmitting their current time at the beginning of the sending message and by comparing time differences between the GPS detector and GPS satellites collected and using constant speed of light property, GPS detector location could be identified (see figure 7).

Since the satellites are moving relative to the detector with a high speed and with a low gravitational field, Relativistic time dilation effect should be taken into the account to do the correction. From relativity, the discrepancy between the atomic clock of GPS satellites and the clock of the earth surface is about 38 microseconds per day(~1.14km)[9]. If we do not correct this discrepancy, this error will be accumulating. To take this into account, the frequency of the atomic clock of each satellite is given a rate offset before launch, making it run slightly slower than the clock on the Earth(specifically, offset it to be 10.22999999543 MHz instead of 10.23 MHz)[10].

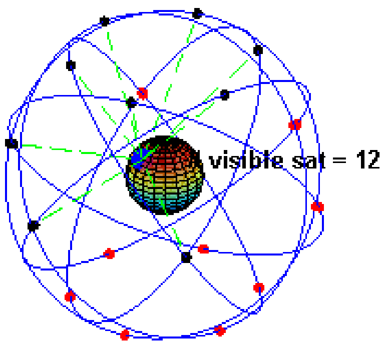

Figure 6: GPS satellites orbits(black in color dots are the GPS detector nearby satellites)

Creator: E1 pak
http://en.wikipedia.org/wiki/Wikipedia:Featured_picture_candidates/Animated_representation_of_the_orbit_of_the_GPS_system. Accessed: 26 February 2008

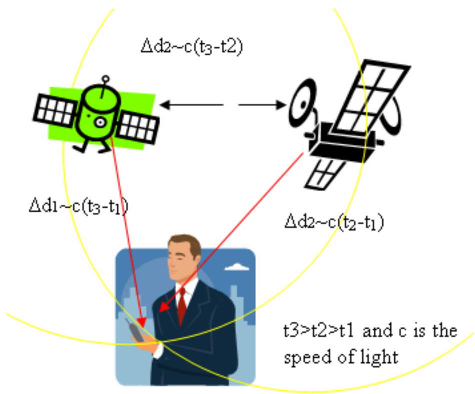

Figure 7: GPS position determination (over simplified)

Summary

There are many other types of satellites classified according to their usage and orbits. In this essay, I have described geostationary and polar orbit satellites and discussed the principle of use of satellites in communication, weather forecast, and global positioning systems. In addition to these, satellites can also be used for scientific research, but discussion of those applications is beyond the scope of this essay.

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