The Global Positioning System by **Dr Nick Stapley** on 25-2-2022

Dr Stapley began by saying it all began in 1957 with Sputnik. This only transmitted single frequency beeps which enabled its orbit to be worked out by measuring the Doppler shift as it passed overhead, using several stations. Later it was realised that with a system of satellites it would be possible to work out where you were on earth.

The first positioning satellite system, with five satellites, was developed in 1960 by the US Navy so that their nuclear submarines could check their position with an hourly fix when they surfaced.

In 1967 atomic clocks were shown to work in space, and in 1973 the Pentagon established the DNSS, later renamed NAVSTAR Global Positioning System, then just GPS. The first GPS satellite was launched in 1975, the full complement of 24 by 1994, comprising four satellites in each of six orbits.

Orbits are semi-synchronous at 20,200 km (12,550 miles) altitude (about 20,600 km radius from the centre of the Earth), a complete orbit taking 12 hours.

The system was commissioned in 1995, and provided 24/7 coverage. The original satellites had a design life of 7.5 years (though some worked for 20 years); the latest have 15 years design life. In 2011 the number of satellites was raised to 27. There has been a steady replacement policy since, as satellites fail; later satellites having extra functionality.

Each satellite transmits messages with the time the message was sent and information enabling the position of the satellite to be determined when it sent the message. A GPS receiver can measure the time it receives the message and calculate its distance from the satellite. It needs to have at least four satellites in sight, to determine its position. There is an unknown delay between the (synchronised) satellite clocks and the GPS receiver clock, and the latitude, longitude, and altitude are also unknown. Each satellite provides an equation so with four unknowns four simultaneous equations (one from each satellite) give the position. Atmospheric conditions introduce most of the error in the system.

The speed of light is 299,792,458 m/s in vacuo by definition, slightly lower in air but near enough to 300 m/μs. Accurate timing is crucial. Messages are transmitted in what was then called the L Band (1 – 2 GHz).

Satellite clocks will not keep in time with ground-based clocks due to relativistic effects: a clock at high altitude, where gravity is lower, will run faster than at ground level. It will need frequent corrections from the ground to avoid the build up of a 38μs error per day (equivalent to about 11km/day in position). The satellite actually transmits slightly offset frequencies so that the received frequencies are as stated.

Dr Stapley described the system in terms of three segments: *Space*, *Control*, and the *User*

Space segment – There have now been 5 generations of satellite: all providing the same basic service.

- The first was launched from 1990-1997, the last of its type only decommissioned in 2019. Messages, on the frequency designated L1 allowed Coarse Acquisition (specifically L1 C/A) by civil users, and precision acquisition by the military on L1 and L2. Coarse acquisition was produced by dithering a precision signal, so that users could only find their position within a few metres – the dithering was switched off in 2000, by order of President Clinton, when ways of improving the precision were found, despite having coarse signals.
- An improved design was used from 1997-2004.
- The third generation introduced a military, M, code. It was launched from 2005-2009.
- The fourth generation used an advanced atomic clock, had improved accuracy, and greater signal strength. A new frequency, L5, was added for civil use (radio Hams). It was launched from 2010-2016.
- The fifth generation was another step up, and includes a Safety of Life (search & rescue) payload. It was first deployed in 2018.

Other frequencies – L3, used for Nuclear detonation detection to check for nuclear test ban violations.
- L4, used in a study for ionospheric corrections.
- L5, used for Safety of Life.

Messages – the satellites send Navigation Messages at a rate of 50 bits per sec, which take 750 sec (12.5 min) to send. A complete Message comprises 25 Frames of 1500 bits. Each Frame has 5 Subframes of 300 bits.
- Subframe 1 is for the satellite Clock and GPS Time relationship;
- Subframes 2 & 3 state the satellite Orbit (ephemeris);
- Subframes 4 & 5 give coarse orbital information (the almanac), and atmospheric error corrections for all satellites. These are too big for a single pair of subframes, and occupy (are commutated between) 25 pairs of subframes. Whence the need for 25 Frames per message.

As Satellites have a limited transmission power, the slow message rate enhances the signal receivability.

Control segment – Ground based equipment, consisting of:

- The Master Control Station (MCS) at the Schriever Air Force Base, Colorado – with alternate master control at the Vandenberg Air Force Base, California.

  The MCS provides command and control for the GPS satellite 'constellation'. It Receives navigation information from the Monitor Stations and uses this to compute the precise locations/orbits of the GPS satellites and generates and uploads clock time corrections and orbital data/navigation data. It Monitors system integrity and determines the health status of the satellites - in the event of a satellite failure it can reposition satellites to maintain an optimal GPS constellation.
- Ground Antennas operated by the MCS – there are four, at Cape Canaveral and one each on islands in the Atlantic, Indian & Pacific Oceans.
- Monitoring Stations - There are 16 located around the world: six operated by the MCA, and ten by the National Geospatial Intelligence Agency (NGA). They have sophisticated GPS receivers. These track the GPS satellites as they pass overhead and send their observations back to the MCS. They also collect atmospheric data, range/carrier measurements, and navigation signals.

Sources of Errors – There are many sources of error other than timing differences:

- Passage of signal through Ionosphere (charged particles)
- or through Troposphere (water vapour)
- Multipath (message received from a reflected signal)
- Modelling error
- Satellite and Receiver clock errors
- Receiver Noise
- Ephemeris (Orbital) error
- Visibility of Satellites
- Bunching of Satellites - Geometric Dilution of Precision Multiplier (DOP) – least with 3 satellites around the horizon and one overhead.
- Deliberate: Selective Availability (turned off in May 2000)

GPS Errors/Error Budget for L1 C/A Typical Error in metres Final error scaled up by the DOP

Per satellite	Standard GPS	Differential GPS
Ionosphere	5.0 – 7.0	0.4
Troposphere	0.5 - 0.7	0.2
Signal arrival (C/A)	2.0 – 3.0	?
Satellite Clock	1.5 - 3.6	0
Orbital Errors	1.0 - 2.5	0
Multipath	0.6 - 1.2	0.6

User segment – The GPS Receiver needs a Processor, and a stable Clock.

- Standard chipsets available are available, for instance from Farnell, a supplier of electronic components. A GPS chip is no larger than the nail of one's little finger. Mobile phones equipped for GPS are available.
- The receiver, when (the phone is) on, receives messages from all the satellites overhead, and builds up a memory of which satellites are likely to be available (these will be in a limited number of orbits).
- The user can then select which messages to download - the code of a likely satellite can be tried and, if successful, its message received. The process can be repeated until one's location is obtained.
- It is better to get messages from widely spaced satellites. (If working in a limited area and time span, the same set of satellites can be reused.)
- Location of one's position as a point on a map can be plotted using an app which can be put on the phone.

Modern smartphones have a GPS chip. Dr Stapley has one and showed screenshots from the 'GPS Test' app showing location as an Ordnance Survey grid reference, and satellite information. The latest Ordnance Survey maps have a code (under a silver scratch-away part) which enables you to download the map you have bought to your phone. He used the associated Ordnance Survey phone app which shows you where you are and in which direction you are facing, and allows you to zoom in and out, showing screenshots from a visit to Leatherhead Common.

Enhanced Accuracy

- Use more frequencies.
- Use more satellites, or satellites of other systems (eg GLONASS, the Russian system).
- Differential GPS – A receiver placed at precisely known location may get a GPS position a short distance away. This distance, and its bearing, can be used to correct other GPS positions in the vicinity to a distance of perhaps 150 miles.
- Carrier Phase GPS (CPGPS). The carrier phase of L2 and all the information of the L1 message can give an accuracy of a few mm.
- Relative Kinematic Positioning/RTK, where movement of the receiver (eg on a ship) can be compensated.

And for the user on the ground with the appropriate apps:

- Differential Global Positioning System (DGPS) has a network of fixed ground stations used to enhance the accuracy of location data collected by a GPS receiver.

- DEM is a digital data set of terrain elevations for regularly spaced ground locations (GPS elevations are generally three times less accurate than ground positions).

Best accuracy now enables real time tracking of tectonic plate movements.

Other Systems:

- GLONASS (Russia) 1995 and 2011 - 24+3 Satellites
- GALILEO (EU) Planned for completion in 2020 - 27+3 Satellites
- BeiDou / COMPASS - 10 Satellites in Geostationary orbit to be expanded (COMPASS) to 35 by 2020
- IRNSS (India) - 7 Satellites planned in Geostationary orbits
- Quazi-Zenith (QZSS) (Japan) - 3 Satellites for communications and navigation.

TIME STANDARDS and RELATIVITY

Coordinated Universal Time (UTC). GMT is now a time zone based on UTC. Leap seconds are inserted at irregular intervals as the Earth slows down. It deviates from TAI by a whole number of seconds.

International Atomic Time (TAI) – This is the primary international time standard from which other time standards, including UTC, are calculated. It is based on the combined input of some 400 atomic clocks around the world, corrected for gravity. It is now 37s ahead of UTC (TAI - UTC = 37s); it was established in 1972 to be 10s ahead of UTC, since when 27 leap seconds have been added.

"GPS Time" was aligned with UTC on 5/6th January 1980, but is kept 19s behind TAI and is now (17 Jan 2022) 18 seconds ahead of UTC.
The largest time unit used is the week consisting of 604,800s. It uses a "Z-count" based on internally derived "Epochs" of 1.5sec, presented as 29 bit binary number. The 10 MSBs (most significant bits) of the Z-count are the week number, from 0 to 1023.

The 19 LSBs are the time-of-week (TOW) = number of epochs since last week transition. At the end of week 1023 the week will become week 0 again – 19.6 year cycle