Senior and Master Air Cadet

Satellite and Data Communications

Module (Learning Outcome) 2:

Know the components and principles of the Global Positioning System (GPS)

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Module 2 Learning Outcomes

- Know the **components** and **principles** of the **Global Positioning System**, including:
  - How GPS works.
  - The Components of GPS.
  - Constellation of GPS satellites.
  - Ground stations.
  - GPS in the military.
  - GPS in everyday life.

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Lessons

1. Introduction to GPS.
2. GPS system components.
3. How GPS works.
4. GPS in everyday life.

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Satellite & Data Communications

Lesson 6:

Introduction to GPS

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Introduction to GPS

- In this lesson you will be introduced to GPS and learn about:
  - Global Satellite Navigation Systems.
  - The History of the Global Positioning System.
  - GPS Positioning Services.
  - Basic Method of GPS Operation.

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Global Navigational Satellite Systems (GNSS)

- The Global Positioning System (GPS) was the first Global Navigational Satellite System (GNSS) to be put into service.
- It is owned by the United States (US) government and operated by the US Air Force.
- GPS is a space-based radio-navigation system that provides:
  - Precise 3-dimensional **positioning** (latitude, longitude and altitude), to about 1 metre accuracy.
  - Precise **timing** information, to nanosecond accuracy.
- A GPS receiver connected to a GPS antenna can be used to determine any user's position:
  - Continuously.
  - Anywhere on (or above the) Earth.
  - Under any weather conditions.
  - At no direct cost to the user.

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The History of GPS

- In the early 1970s, during the cold war, the US Department of Defense (DoD) wanted a robust and accurate system to guide submarine-launched Intercontinental Ballistic Missiles.
- The DoD launched its first NAVSTAR (Navigation Satellite Timing And Ranging) satellite in 1978.
- The system became fully operational in 1993, and became known as the Global Positioning System (GPS).
- In the 1990s GPS had a Selective Availability (SA) feature that intentionally degraded GPS' accuracy when used by civilians, for US national security reasons.
- In 2000, the US Government ended its use of SA to make GPS more usable by civil and commercial users worldwide.
- GPS' accuracy is now the same for both civilian and military GPS services.

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GPS Positioning Services

- A GPS receiver can determine:
  - The time, very accurately.
  - Its distance from any given GPS satellite from which it is receiving a signal.
  - Its own position (through triangulation of signals from multiple satellites).
- GPS provides two levels of positioning accuracy:
  - The **Standard Positioning Service (SPS)** is available to all users for peaceful civil, commercial and scientific use.
  - The **Precise Positioning Service (PPS)** is reserved for military use, and other use authorised by the US government.
    - Users receive encryption keys from the US DOD to access the PPS.
    - Should a PPS receiver have not valid encryption keys, it can still behave as an SPS receiver.

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Basic Method of GPS Operation

- The principle of GPS satellite navigation is that of one-way passive ranging, by time difference, based on:
  - Each satellite knowing, and transmitting, its position above the earth.
  - Radio wave propagation (the speed at which radio signals travel through space is known).
  - Precise timing (distance = speed x time; high accuracy in time means high accuracy in distance).
- A constellation of satellites transmits microwave radio signals containing their position and timing information towards the earth.
- The signals can be picked up by GPS receivers on the ground, at sea or in the air.
- Using the signals from several satellites, the receiver can accurately determine its position.
- If a GPS receiver is receiving signals from at least 4 GPS satellites, then it can calculate its 3-dimensional position to around 1m accuracy.

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Satellite & Data Communications

- Lesson 7:
- **GPS Systems Components**

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System Components

- In this lesson you will learn about the components of the GPS, including:
  - The Space Segment.
    - Satellite Constellation.
    - Satellite Orbits.
    - GPS Signal in Space.
  - The Control Segment.
    - Master Control Stations.
    - Ground Antennas.
    - Monitor Stations.
  - The User Segment.
    - GPS Receiver Types.

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GPS Segments



Space Segment



Control Segment



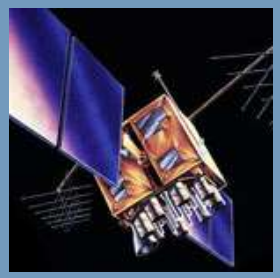
User Segment

Image source: US Government

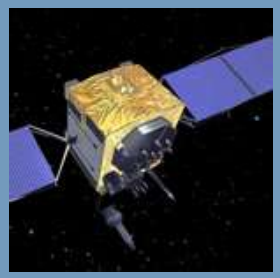
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Space Segment

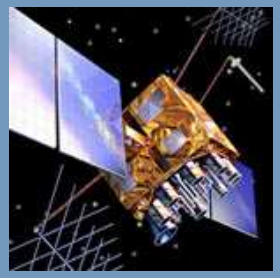
- The space segment comprises a *constellation* of satellites transmitting radio signals to the Earth.
- At the end of 2017, there were a total of 31 operational satellites (not including decommissioned satellites and on-orbit spares).
- The constellation is a mix of old and new generations of satellites:
  - 12 Legacy Block IIR ("Replenishment").
  - 7 Block IIR-M ("Modernized").
  - 12 Block IIF ("Follow-on").
- New Block III satellites are being launched to replace aging ones when needed and to offer higher accuracy and reliability.



Block IIR Satellite



Block IIR-M satellite



Block IIF Satellite

Image source: US Government

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Satellite Constellation

- The baseline operational constellation of 24 satellites is arranged into six orbital planes.
- This arrangement ensures that as the satellites orbit, receivers can view at least 4 satellites from virtually any point on the Earth at any one time.
- Additional satellites are flown to maintain coverage whenever the baseline satellites are serviced or decommissioned.
- The extra satellites may increase GPS performance but are not part of the core constellation.

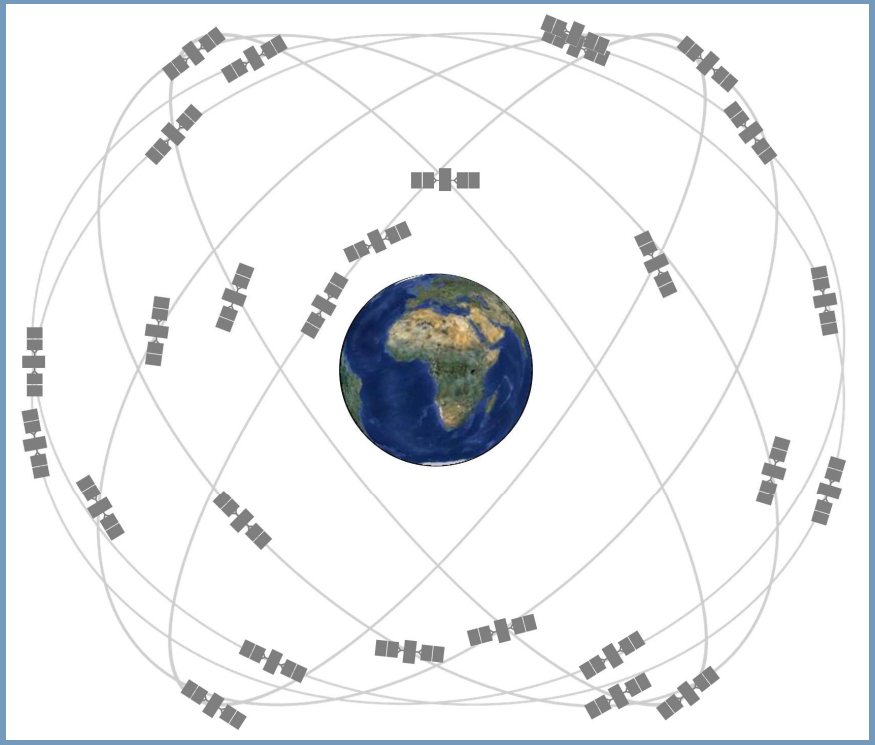


Image source: US Government

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Satellite Orbits

- GPS satellites fly in Medium Earth Orbit at an altitude of 20,233 km.
- This provides optimum ground coverage with the least satellites.
- Orbital eccentricity is very low, almost circular.
- Satellites are distributed evenly, in 6 planes spaced 60° apart.
- Each plane contains 4 orbital slots, occupied by baseline satellites.
- Each satellite has an inclination of 55°.
- Each satellite has an orbital period of 11 hours 58 minutes.

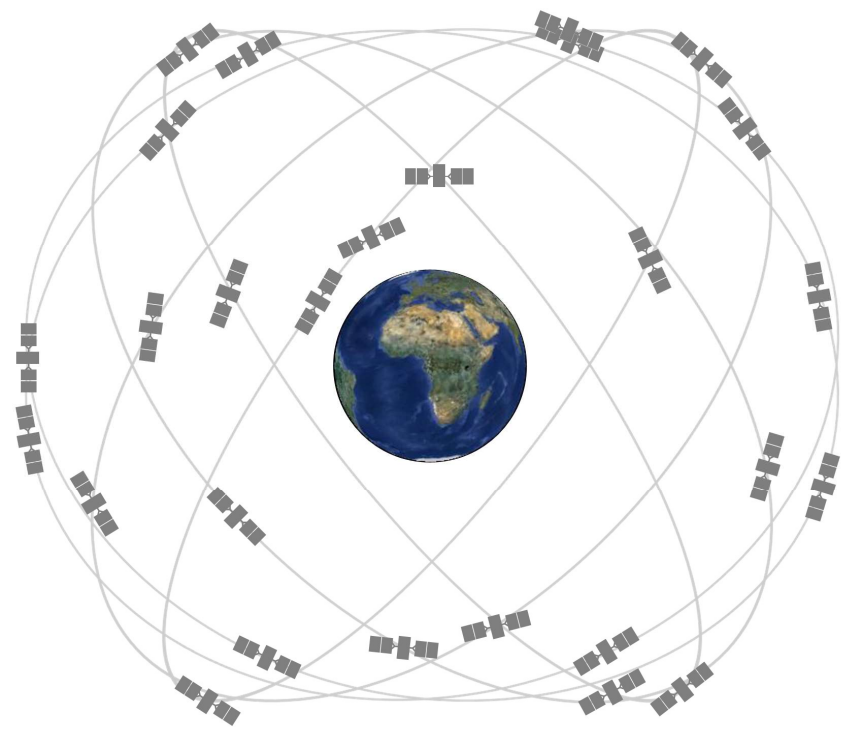


Image source: US Government

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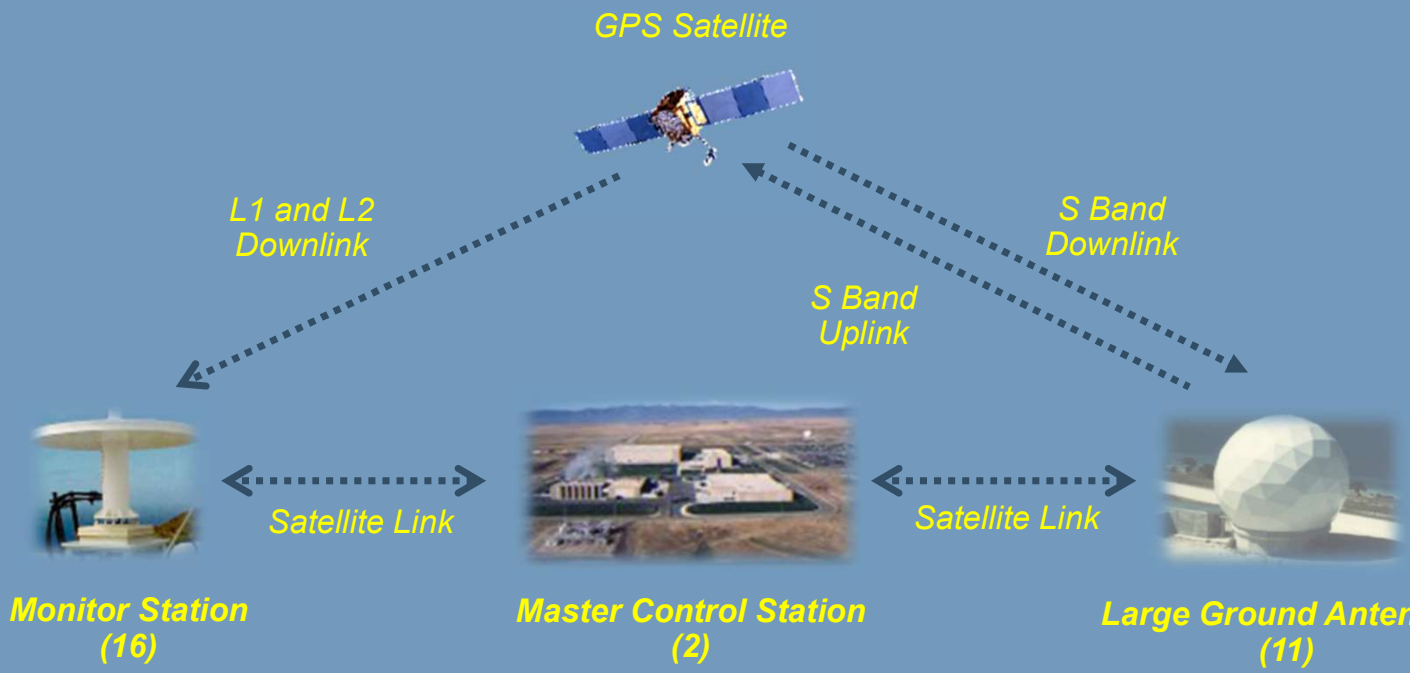
Signal in Space

- Each satellite transmits a microwave radio carrier, called L1, at a frequency of 1575.42MHz.
- The carrier signal is modulated by a number of signal components which provide the satellite's location, the satellite's status, and the precise time (from an on-board atomic clock).
- Two of these components are accessible by all GPS receivers:
  - **A *Coarse Acquisition* (C/A) *code***: a known, time referenced, complex digital code unique to each satellite, that appears like random electrical noise and is used for ranging.
  - **A *Navigation Message*** comprising:
    - ***Almanac data***: a set of orbital parameter data that defines the approximate positions of all the satellites in the constellation. This is used by the receiver during initial acquisition of satellite signals.
    - ***Ephemeris data***: the current satellite position and timing information.
- More carriers and codes are being added over time to improve accuracy and security.

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Control Segment

- The Control Segment is a global network of satellite ground stations, comprising 2 Master Control Stations, 11 Large Ground Antennas and 16 Monitor Stations.



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Control Segment Locations



Image source: US Government

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Control Segment Elements

- *Master Control Stations (MCS)* **command and control** the GPS constellation, to:
  - Compute the precise satellite locations.
  - Generate navigation messages for upload to the satellites.
  - Monitor satellite health and accuracy.
  - Perform satellite maintenance, problem resolution and station keeping.
- *Monitor Stations* are unmanned remote receivers that **continuously monitor** each satellite, to:
  - Track GPS satellites as they pass overhead.
  - Monitor GPS signals and atmospheric data.
  - Feed observations to the MCS.
- Large *Ground Antennas* provide Telemetry, Tracking and Control by:
  - Sending commands, navigation data and software uploads to the satellites.
  - Collecting telemetry from the satellites.
  - Performing ranging on the satellites.

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Control of the GPS System

- GPS accuracy relies on the accuracy of the receiver's clock and knowledge of the satellite's orbital parameters and their atomic clock errors.
- The Control Segment essentially acts as a control loop.
  - It measures the satellite orbit and clock errors as accurately as possible and broadcasts the accurate data to the user receivers via the GPS satellites
  - Monitor stations receive the two navigation signals from each satellite and pass the data back to the MCS.
  - The MCS takes the data from each satellite and updates its estimates of each satellite's orbital parameters and clock errors.
  - The new information is passed to the Ground Antennas for upload to the satellites.
  - When each satellite receives the updates, it will incorporate the new data in subsequent navigation messages.

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User Segment

- The *user segment* comprises all users in possession of a GPS receiver (antenna, hardware and software that processes the navigation signals from the GPS satellites).
- GPS receivers come in various forms and can be used for many purposes, including:
  - **Aviation:** provides 3-dimensional position determination for all phases of flight from departure, en-route and arrival, to airport surface navigation.
  - **Maritime:** provides the fastest and most accurate method for mariners to navigate, measure speed, and determine location while in open sea, congested harbours and waterways
  - **Automotive:** used in vehicles such as cars, trucks and public transport for navigation, location and tracking purposes.
  - **Personal:** available as dedicated handheld navigation devices, or embedded into portable devices such as smartphones.

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Satellite & Data Communications

Lesson 8:

How GPS Works

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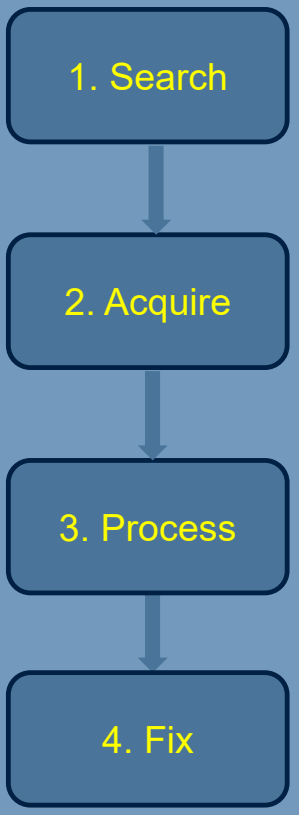
How GPS Works

- In this lesson you will learn how GPS works, including:
  - GPS receiver operation.
  - Measuring time.
  - Measuring distance.
    - Pseudo-ranging.
  - Measuring position.
    - Trilateration.
    - Use of four or more satellites.
  - GPS co-ordinate system.
  - Military GPS.

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GPS Receiver Operation

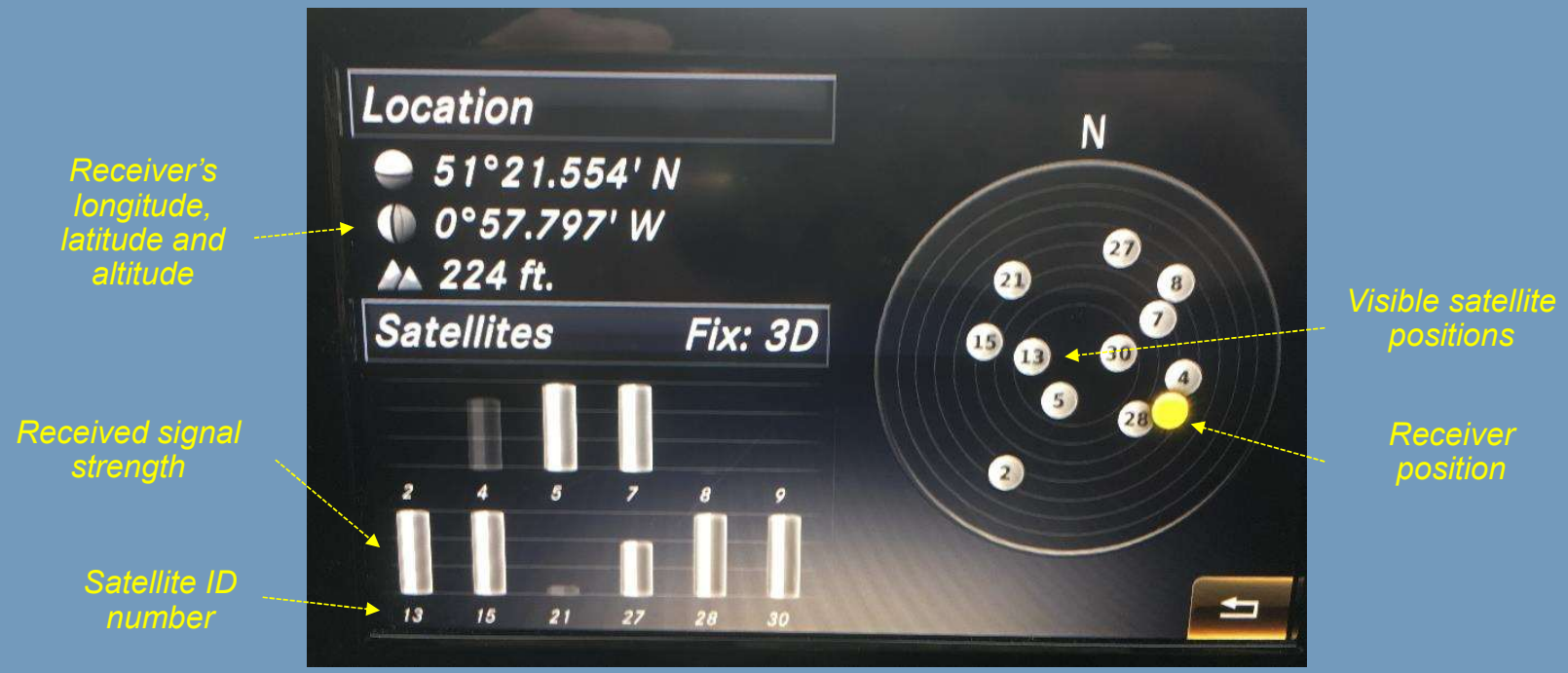
- There are four sequential activities at work in a GPS receiver:
  1. When switched on, the receiver will *search* for GPS signals.
     - This can take about 15 to 45 seconds depending on the type of receiver.
  2. The receiver will examine the signals and *acquire* lock with as many GPS satellites as possible.
     - Receivers with multiple channels can acquire satellites much quicker by processing several satellite signals in parallel rather than in sequence.
  3. The receiver will *process* each signal using built in software, to determine:
     - The time difference between the receiver clock and the satellite precision atomic clock.
     - The distances to each satellite from the receiver.
  4. The receiver will then *fix* the user's position through calculation.
     - Receivers generally provide a fresh navigation fix around once every second.



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GPS Receiver Satellite Fix

- The display shows a typical vehicle GPS satellite navigation receiver with a a 3-D position fix
- The receiver has acquired 7 from 11 visible satellites; ID numbers 5, 7,13,15, 27, 28 and 30



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Measuring Time

- Each GPS satellite is equipped with multiple *atomic clocks* that add extremely precise time data called *Co-ordinated Universal Time* (UCT) to the GPS signals.
- The clocks typically maintain accuracy to 3 nanoseconds (3×10^{-9} seconds) per day, however the relative timing between satellites drifts over time and needs to be corrected by the MCS.
- GPS receivers decode signals transmitted by the satellites, noting their exact arrival time.
- The signal's travel time is the difference between the time broadcast by the satellite and the time the signal is received, about 0.07 seconds.
- Using this information, each receiver can synchronise their internal clocks to the atomic clocks of the satellites.
- This enables receivers to determine the time to within billionths of a second, without the cost of owning and operating atomic clocks.
- Therefore GPS is also an extremely accurate timing system which can be used for clock synchronisation.

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Measuring Distance

- To calculate its distance from a satellite, a GPS receiver applies a simple formula to the satellite's radio signal:

distance = speed x time

- Radio signals travel through space at the constant *speed of light*; 299,792 metres per second.
- The receiver therefore only needs to know the time the radio signal takes to reach the receiver from the satellite in order to calculate the distance to the satellite:

range to satellite = speed of light x signal travel time

- The value derived from this method of computing distance is called a *pseudorange* because:
  - It is not a direct measurement of distance but a measurement derived from time.
  - Not all the errors in the measurement are taken into account.

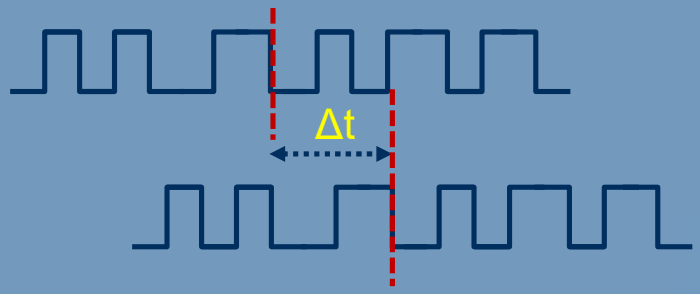
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Pseudoranging

- Starting at exactly the same point in time, the satellite and receiver generate identical *pseudorandom* binary sequences (the C/A code).
  - The codes are unique to each satellite and repeated constantly every 1023 bits.
  - GPS receivers match the C/A code of each satellite with an identical copy of the code contained in the receiver database.
- The satellite transmits its code, but the received version of the code lags behind due to the time taken for it to travel to the receiver.
- The receiver compares its own and the received code to determine the time shift, (Δt).
- (Δt) multiplied by the speed of light gives the distance from the satellite to the receiver.

Synchronously running C/A code at satellite transmitter and receiver

Delayed C/A code received at the receiver



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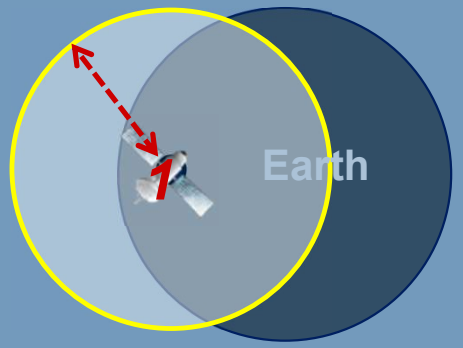
Measuring Position

- Theoretically, to determine the GPS receiver's position at any time, the satellite coordinates of a minimum of three satellite ranges are required.
- The received GPS navigation message includes the *broadcast ephemeris* containing the orbit parameters of the satellites.
- Knowing the satellite's orbit parameters and the current time, it is possible to calculate the exact 3-dimensional position (longitude, latitude, altitude) of the satellites at any point in time.
- By knowing each signal's point of origin and its arrival time, the GPS receiver can compute its own co-ordinates.
- It does this by using a technique called *trilateration* that exploits the geometry of circles and spheres.
- The GPS receiver performs the trilateration computation by constructing imaginary spheres.
- Using this method, GPS can give an instantaneous, real-time position to within approximately 5-10 metres for 95% of the time for civilian users.

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Trilateration - 1st Satellite

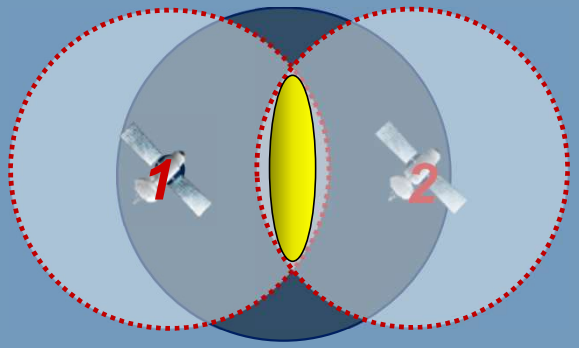
- The first GPS satellite signal pseudoranging tells the receiver how far it is from that satellite.
- The satellite is at the center of the sphere and radius is equal to the measured distance or *pseudorange*.
- The location of the receiver could thus be anywhere on the surface of an imaginary sphere, whether on land, in the air or even in space.



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Trilateration - 2nd Satellite

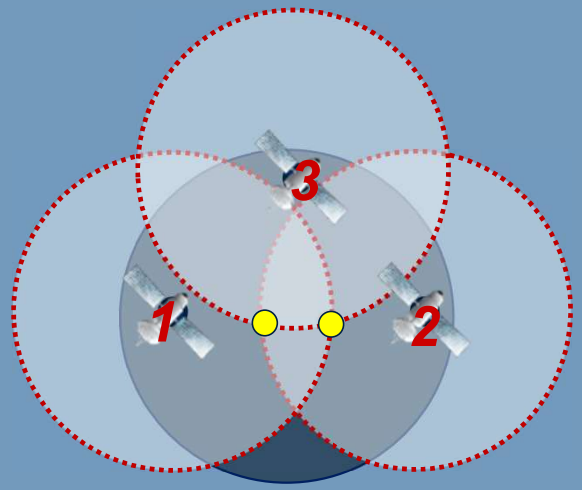
- The second GPS satellite signal pseudoranging creates a second sphere centered on the second satellite
- This narrows down the location of the receiver to somewhere on the circle where those two imaginary spheres intersect.



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Trilateration - 3rd Satellite

- The third GPS satellite signal pseudoraning creates a third sphere centered on the third satellite.
- This further which narrows down the receiver location to two points on the circle where those three imaginary spheres intersect
- One point is obviously wrong as it is usually well above the surface of the Earth, or deep within the Earth, and so can be discarded.



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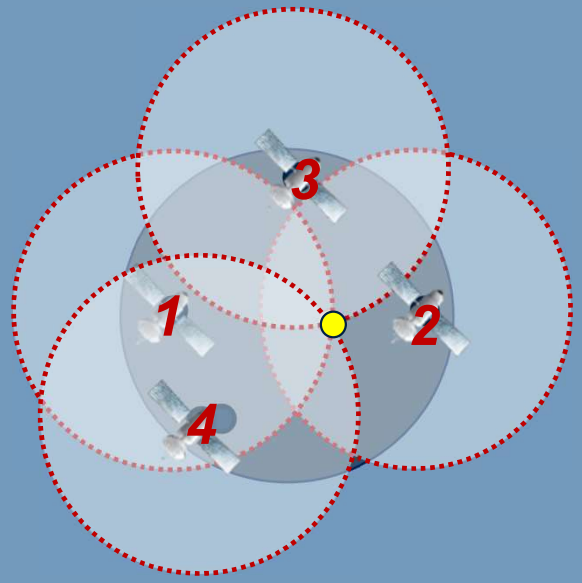
Use of Four or More Satellites

- In practice, GPS positioning requires 4, rather than 3 satellites, to determine 3-D position.
- Receiver's use small, low cost oscillator clocks that are insufficiently accurate to stay perfectly synchronized with the satellite clocks and hence identify a precise location with 3 satellites.
- A 4^{th} satellite accounts for the receiver clock offset causing timing errors, as well as correcting for other errors in the system.
- More than 4 satellite signals received simultaneously would improve the GPS position precision even further, particularly in the vertical position.
- The receivers process the extra signals using special statistical techniques to correct for any remaining errors. This brings the receiver's clock back into synchronisation with the satellite's precise atomic clock.
- Most modern receivers consist of 12 separate channels which can track and process data from 12 satellites in parallel to acquire them more quickly.

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Trilateration - 4th Satellite

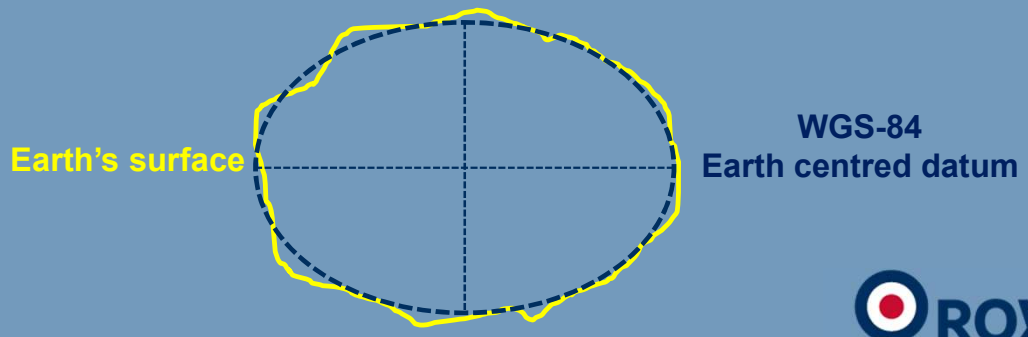
- If all the pseudoranges were absolutely precise based on accurate time measurements, then a fourth satellite measurement would coincide with the single point of intersection from the other three, but in reality it rarely does.
- The receiver makes an adjustment by searching for a single correction to all four timing measurements such that the 4th satellite measurement gives the same position as the other three.
- The receiver clock can then be synchronized to the satellite atomic clock.



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GPS Co-ordinate System

- The earth is not a perfect circle; it bulges at the equator and is squashed at the poles.
- To account for this, GPS uses the US National Geospatial Intelligence Agency model of the Earth called the *World Geodetic System 1984* (WGS-84) as the reference coordinate system to determine latitude and longitude.
- The model provides a description of the shape of the earth and overcomes the problem of using many different geodetic datums worldwide.
- The GPS receiver employs an algorithm in the receiver to transform the orbit parameters of the GPS satellites received from the broadcast ephemeris into WGS-84 format.



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Military GPS

- Military GPS is used where accuracy and reliability is critical, such as locating friendly forces and precision munitions guidance.
- Military receivers use the *Precise Position Service* (PPS) to work around potential vulnerabilities such as:
  - *Spoofing;* imitating the GPS signal to cause false readings.
  - *Jamming;* interference to prevent GPS signal reception.
- To prevent spoofing, an alternative encrypted *P[Y] code*, is transmitted on the L1 carrier to ensure that an authentic signal is being received.
  - Only US and its allies have access to the encryption keys to decode the P[Y] signal.
- To prevent jamming, the P[Y] code is also transmitted on an additional carrier called L2 at a frequency of 1227.6 MHz



Precision Lightweight GPS Receiver (PLGR)

Image courtesy of jc⁴i

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Satellite & Data Communications

Lesson 9:

GPS in Everyday Life

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GPS in Everyday Life

- In this lesson you will learn about how GPS is used in everyday life, including:
  - Public Safety.
  - Surveying, Mapping, and Geodesy.
  - Geophysics.
  - Land Transportation.
  - Earth Environmental Sciences.
  - Scientific Research and Exploration.
  - Recreation.

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Positioning, Navigation, Timing

- GPS receivers are employed by a wide range of users to meet their daily needs.
- The term *PNT* is commonly used to describe the services that GPS provides, or to denote the various methods and technologies by which navigation is supported.
  - *Positioning* is the ability to accurately and precisely determine location and orientation for mapping and tracking purposes.
  - *Navigation* is the ability to determine current and desired position and apply corrections to course, orientation, and speed to attain a desired position anywhere around the world, from sub-surface to surface and from surface to space.
  - *Timing* is the ability to acquire and maintain accurate and precise time from a *Universal Time Clock* (UTC) anywhere in the world and within user-defined parameters.

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Cadet Activity

- Cadets should research and discuss what they know about the GPS system and its many uses, both from their own experiences and using the Internet.

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Public Safety

- GPS serves as a facilitating technology to assist *public safety* and *disaster response* teams as they respond to emergencies and prepare for the unexpected.
- First responders such as law enforcement, fire fighters and emergency medical personnel rely on GPS to provide critical instant location and route information.
- Knowing the precise location of landmarks, streets, buildings, and emergency service resources shortens travel times, allowing quicker responses often meaning the difference between life and death or significantly mitigating property damage and loss.

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Surveying, Mapping and Geodesy

- GPS provides many advantages for *surveying,* compared to traditional mapping and surveying techniques by not requiring a line of sight between adjacent surveyed points:
  - Accuracy is improved.
  - Unaffected by weather.
  - Collection is much faster and the amount of equipment and labour required is reduced, leading to cost savings.
- *Geographic Information Systems* (GIS) can be used to;
  - Display features, store, manipulate, and display geographically referenced data measured with GPS on maps.
- *Geodesy* is the science of accurately measuring and understanding the Earth's geometric shape, orientation in space, and gravity field, as well as changes to these properties over time.
  - By using GPS, the movement of a site can be continuously and accurately monitored.

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Land Transportation

- All modes of land transportation, including trains, trucks, automobiles, all terrain vehicles have applications in which safety, position-location, and navigation are important.
- *Automatic Vehicle Location* (AVL) using GPS is a means for determining the location of a vehicle and transmitting this information to a point where that data can be used to manage vehicle fleets, public transportation, delivery trucks and courier services.
- *Tracking* can provide an historical record of driving habits or events providing benefits such as routing efficiency, fuel efficiency and maintenance costs, driver monitoring, safety and security and asset monitoring
- *Automatic guidance* of farm vehicles allow farmers to apply precise amounts of fertilizer and pesticide to exact field locations based on crop type planted and soil composition, potentially improving both the efficiency and cost-effectiveness of these operations.

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Vehicle Navigation

- *Vehicle navigation* systems use a *moving map display* as a type of navigation system output.
- Instead of numerically displaying coordinates from the GPS receiver, or a heading and distance indication of a certain waypoint, it displays the receiver's current location at the centre of a map
- As the receiver moves and new position coordinates are determined, the map moves to keep its position at the centre of the display
- The display portrays the receiver's physical movement, typically showing a simulated overhead view of the location on a moving map.
- Some devices also simulate a 3D view from the perspective of the receiver.



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Earth Environmental Sciences

- Our ability to measure the land, ocean and atmosphere has been greatly enhanced by GPS.
- **In *meteorology***, GPS receivers are mounted on weather *sounding balloons* to measure atmospheric water vapor.
- **In *atmospheric science***, GPS receivers are mounted on *Ozonesondes (*lightweight, balloon-borne instruments) to monitor holes in the ozone layer.
- **In *oceanography***, GPS receivers are mounted on *buoys* used to:
  - Observe the effects of ocean tides.
  - Track the movement and spread of oil spills.
- **In *geodynamics***, to study relative motions on the surface of the Earth to monitor earthquakes.

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Scientific Research and Exploration

- GPS is used for many different scientific research and exploration purposes that require accurate and reliable positioning.
- **In *archaeology***, fieldwork GPS receivers may be used to map find-spots, earthworks and other archaeological features without the need of conventional techniques.
- ***In biology***, animals can be equipped with GPS technology to;
  - Obtain accurate locations that can be combined with sensor data to study animal behaviour.
  - Track and map the migratory patterns of endangered species as they migrate to another habitat for a season, move in search of food or shelter, or are forced out of their ecosystem by human activity such as construction, thus helping to preserve and enhance declining populations.
- ***Explorers*** can carry GPS receivers to:
  - Easily locate themselves and their findings
  - Navigate in remote, uncharted territory.

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Recreation

- Personal GPS receivers are used mostly for transportation-related activities involving both vehicles and pedestrians.
- **In *recreation***, GPS can be used for:
  - “Off-roading" with four-wheel drive vehicles.
  - Back-country skiing.
  - Hiking and mountain climbing.
  - Bicycling.
  - Boating.
  - Even golfing.
- For those activities in which the potential for getting lost is high, and search and rescue can be required as a result, GPS is much more than a useful gadget; it is potentially life-saving.

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Cadet Activity

- Cadets should experiment with as many types of GPS equipment as possible; for example, mobile phones, in-car navigation, walking handsets.
- Cadets should discuss how they operate and are used and identify the advantages and limitations of their use.

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Summary of Module (Learning Outcome) 2

- You should now know the components and principles of the Global Positioning System, including:
  - How GPS works.
  - Components of GPS.
  - GPS satellite orbits.
  - Ground stations.
  - GPS in the military.
  - GPS in everyday life.

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