Dar es Salaam Institute of Technology (DIT)

ETU 08222

Radar and Navigational Aids Systems

Ally, J

ICT Professional (Radio Frequency Communication)

Huawei Certified Academy Instructor (Datacom, Cloud Computing, Storage, and 5G)

jumannea@gmail.com

Global Navigation Satellite Systems (GNSS)

Introduction

- **Global Navigation Satellite System (GNSS)** is a generic reference for any navigation system based on satellites.
- The system in widespread use today is the United States' Global Positioning System (GPS).
- Other types of GNSS include the Russian global navigation satellite system GLONASS and European System Galileo.
- Satellite navigation has become the mainstay of all global navigation systems and is an indispensable tool in modern aviation.
- The convenience of use and relatively low cost of the user equipment has led to the installation of GNSS navigation receivers in virtually all aircraft from gliders to commercial jet transport.
- Increasingly, procedures are being implemented for aircraft to **approach and land** using GNSS as well as navigate enroute so that in the near future it is likely that most flights can be conducted using only satellite navigation.

GPS Overview

- The US GPS was initiated in 1973 and referred to as Navstar (**n**avigation **s**atellite with **t**iming and **r**anging).
- The system was developed for use by the US military; the first satellite was launched in 1978, and the full constellation was in place and operating by 1994.
- GPS is now widely available for use by many applications including aircraft navigation.
- The system comprises a **space segment**, **user segment** and **control segment**.
- Twenty-four satellites **(the space segment)** in orbit around the earth send data via radio links that allow aircraft receivers **(the user segment)** to calculate precise **position, altitude, time and speed on a 24-hour**, worldwide, all-weather basis.
- The principles of satellite navigation are based on **radio wave propagation**, precision timing and knowledge of each satellite's position above the earth; this is all monitored and controlled by a network of stations **(the control segment).**

Basic Principle of Satellite Navigation

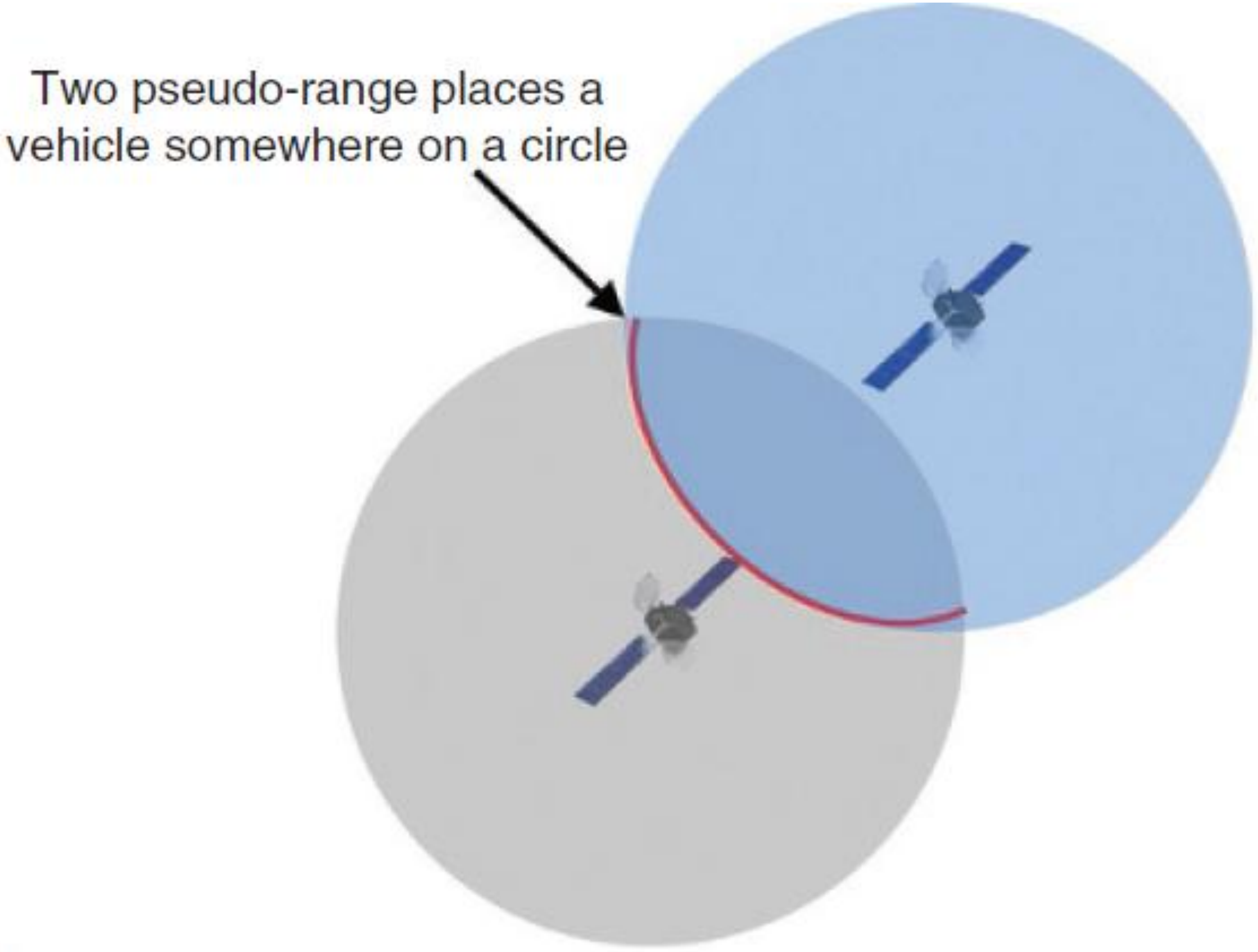
- A GNSS system employs a constellation of satellites orbiting the Earth so that a vehicle always has line of sight with several of them.
- Each satellite has an atomic clock on board that is synchronized to the clocks on the other satellites and to atomic clocks on the ground that define “GPS time,” which is also synchronized to Coordinated Universal Time (UTC).
- Each satellite continuously broadcasts its current orbital position (ephemeris) with each broadcast starting at a precise time referenced to GPS time in a similar manner to UTC.
- Then knowing the time that the message was sent and the position of the satellite at that time, both of which are contained in the message, the time for the signal to reach the vehicle and thus the distance to the satellite would be known.
- A single satellite would define the position of the vehicle as somewhere on the surface of a sphere.
- Two satellites would **fix the position** as somewhere on the circle where the spheres intersect and three would place the vehicle at one of two points, one near the surface of the Earth and the other out in space, which can be discarded.

Basic Principle of Satellite Navigation (2)

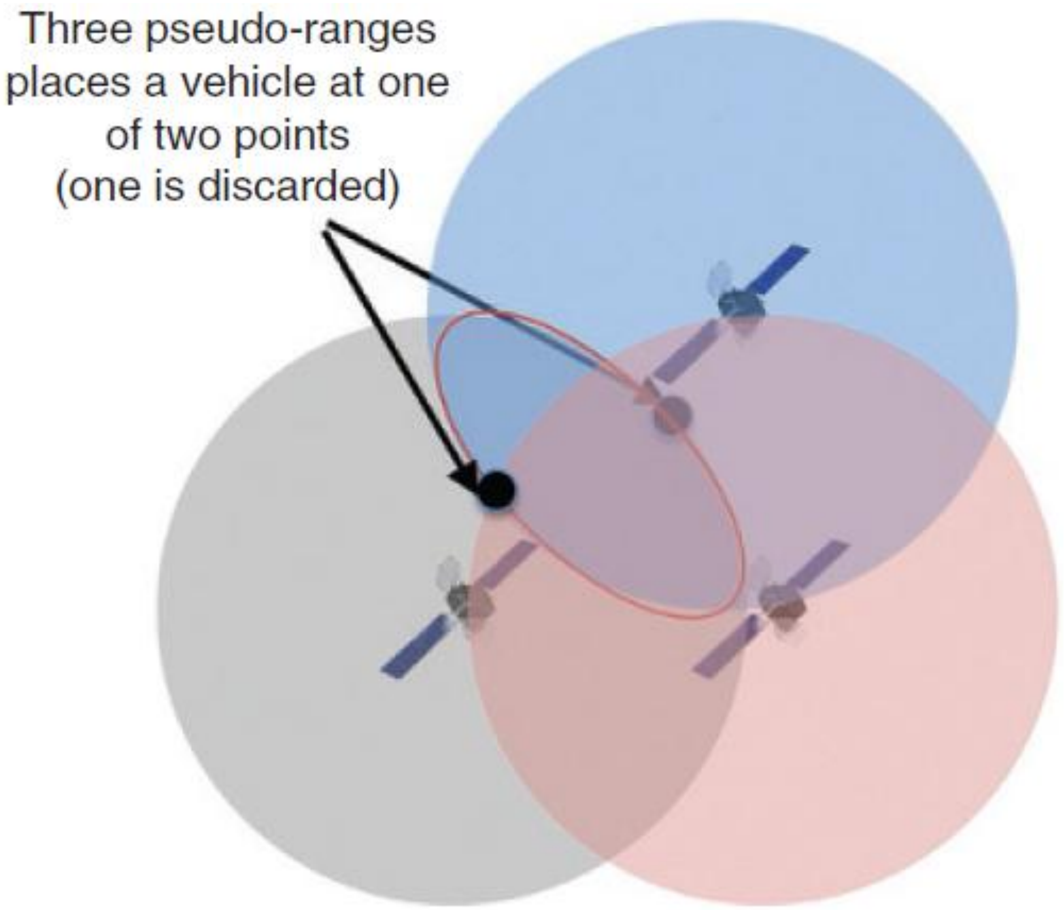
- The aircraft, however, does not have an atomic clock synchronized to GPS time and although modern quartz clocks can be extremely accurate for normal purposes each microsecond offset from GPS time will produce a 300m error in the calculated distance.
- The inaccurate distances obtained without synchronizing the aircraft clock to GPS time are termed **pseudo-ranges**.
- Bearing in mind that that all the satellite clocks are synchronized, the time offset between the aircraft and satellite clocks is the same for all satellites.
- Thus, receiving the signals from a fourth satellite enables the construction of four simultaneous equations for four variables, that is, the **three pseudo-ranges** and the **time offset** between the satellite and aircraft clocks.
- Knowing this fourth variable allows the aircraft clock to be synchronized to the satellite clocks and thus the pseudo-ranges can be converted to absolute distances with high accuracy.
- A by-product of the process is that the GNSS receiver is synchronized to GPS time and thus to UTC with **atomic clock accuracy**.
- It is not feasible to solve the four simultaneous equations in real time at the rate at which the signals are received from the satellites and in practice preprogrammed filters are used to stream out positional data in response to the input data arriving from the satellites.

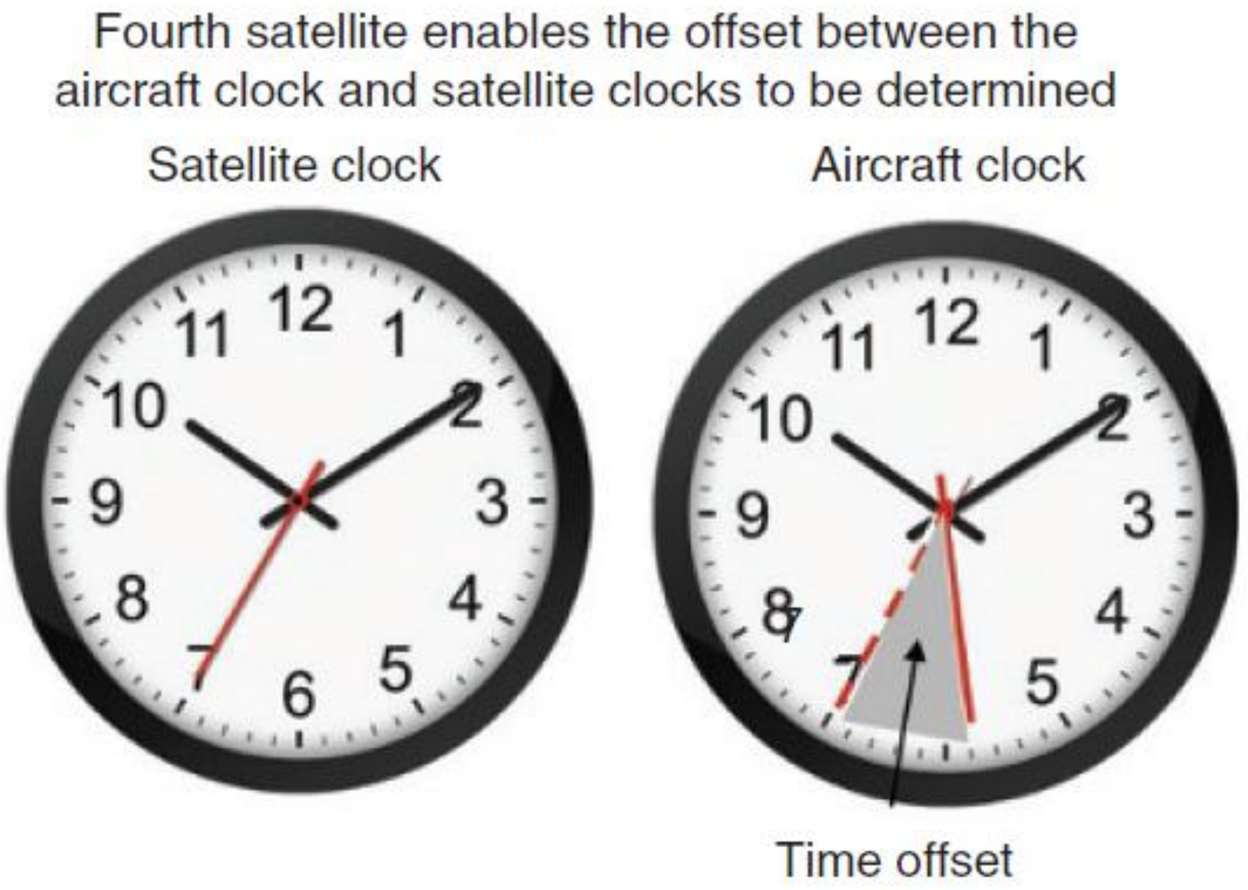
Principle of Position Determination by GNSS

One pseudo-range places a vehicle somewhere on a sphere



Principle of Position Determination by GNSS





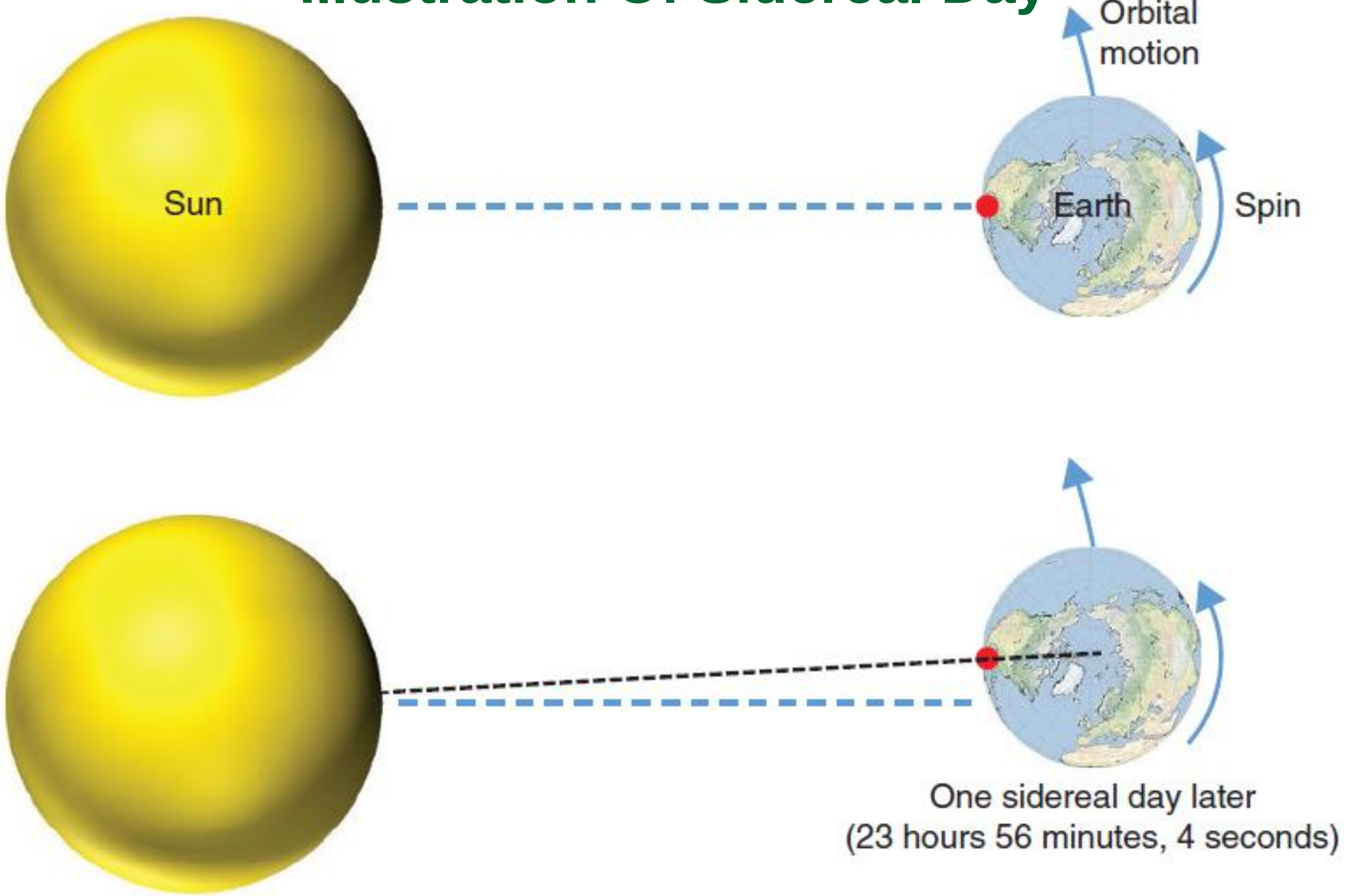
The Constellation of Space Vehicles (SVs)

- The group of satellites or **Space Vehicles (SVs)** that are at the heart of a satellite navigation system are described as a constellation and they transmit in the **UHF band**, so reception will only occur along **the line of sight**.
- Thus, the first aspect of the design that needs to be addressed is how many satellites are required and in which orbits to ensure that **at least four** are visible at all times from anywhere on the Earth's surface.
- **As the more satellites** that are in view, **the more accurate the position fix** and in addition, having more than four in view enables error checking and monitoring of the integrity of the system.
- The constellation described in detail here is the US Navstar system that is more commonly known as the **Global Positioning System (GPS).**

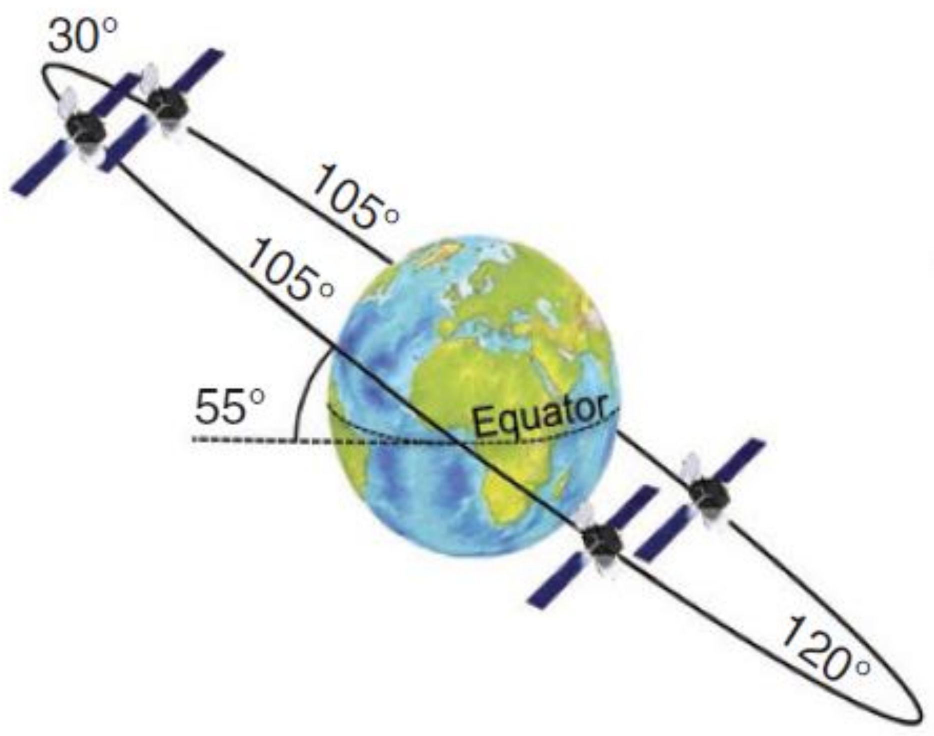
Orbital Radius of the GPS Constellation

- The basic GPS system uses **24 satellites** that are placed in an orbit such that **each satellite** makes exactly **two rotations about the Earth** for one rotation of the Earth about its axis.
- The relevant Earth rotation period is the time taken to turn once relative to the distant stars, that is, the sidereal day, which is **23 hours, 56 minutes, and 4 seconds (86 164 seconds).**
- It is slightly shorter than the mean solar day, which is the period between the Sun appearing overhead on consecutive days.
- The difference is due to the fact that after completing one sidereal rotation, the Earth has moved in its orbit around the Sun so it has to rotate a little further for the Sun to appear overhead.
- The Earth is in an elliptical orbit about the Sun so the length of the solar day changes slightly due to the speed of the Earth varying in its orbit, which is why the mean solar day needs to be specified and is the period in common use.
- Thus, the GPS satellite orbital period is half a sidereal day, which is 11 hours, 58 minutes, and 2 seconds (43 082 seconds).

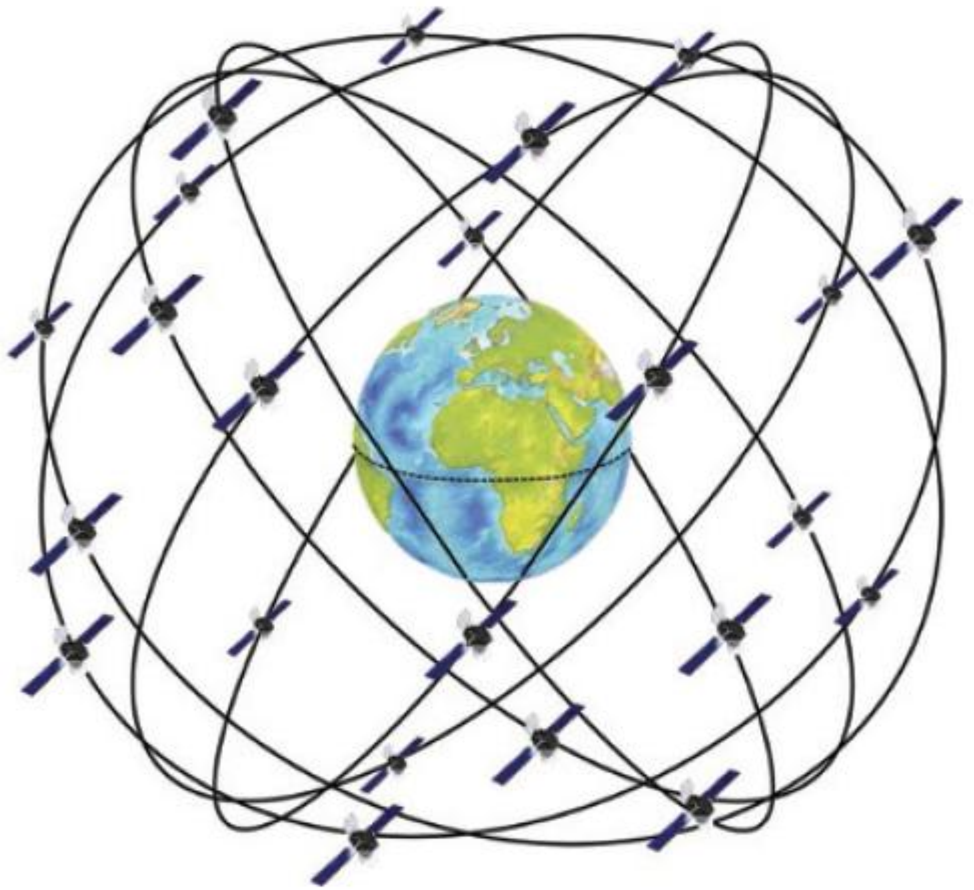
Illustration Of Sidereal Day



Orbital Arrangement for Optimal Coverage by the GPS Constellation



Each orbital plane is aligned at 55^0 to the equator and contains four satellites with the angular spacings shown.



There are six orbital planes separated by 60^0 containing the constellation of 24 satellites.

Orbital Radius of the GPS Constellation (2)

- It is straightforward to calculate the radius of the orbit to achieve the required orbital period. A stable obit occurs when the centripetal force equals the gravitational attraction between the Earth and the satellite, that is:

$$\frac{GM_{\oplus}m_s}{r^2} = \frac{m_s v^2}{r}$$

Where $M_{\oplus}$ is the mass of the Earth, m_s is the mass of the satellite, v is its velocity, r is the radius of the orbit, and G is the gravitational constant (= $6.67408 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$).

- The above equation simplifies to: $$v = \sqrt{\frac{GM_{\oplus}}{r}}$$
- The length of the orbit is 2πr and thus the period is $\tau = 2\pi r/v$, that is: $$\tau = \frac{2\pi r^{3/2}}{\sqrt{GM_{\oplus}}}$$
- so, the radius required to achieve a given period is:

$$r = \left(\frac{\tau^2 GM_{\oplus}}{4\pi^2}\right)^{1/3}$$

GPS Segments

- The current GPS consists of three major segments.
- These are **the space segment**, **a control segment**, and **a user segment**.

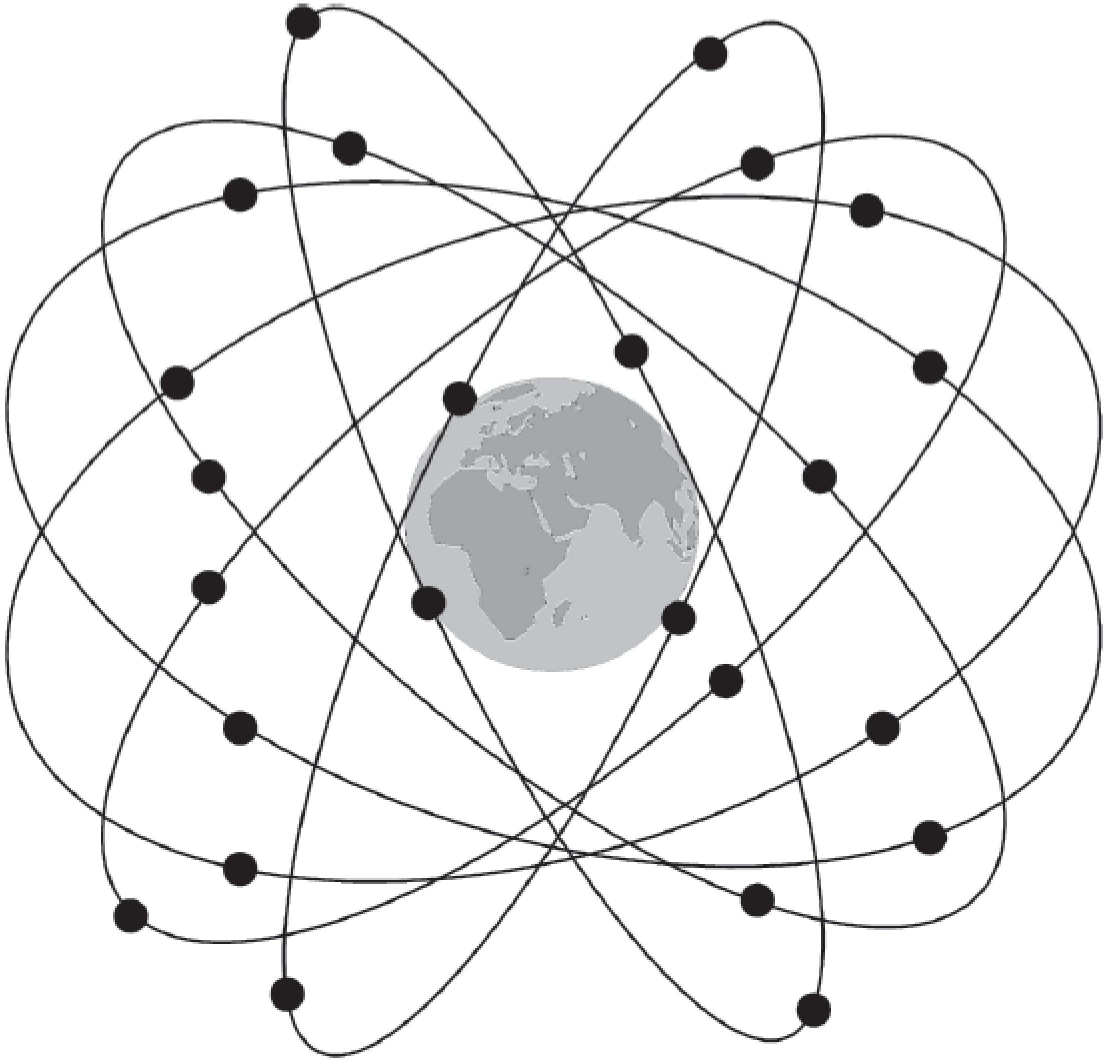
  (Note that the GPS is being updated and modernized with next generation satellites, alternative radio frequencies and higher specifications).
- The U.S. Space Force develops, maintains, and operates the space and control segments.
- GPS satellites broadcast signals from space, and each GPS receiver uses these signals to calculate its three-dimensional location (latitude, longitude, and altitude) and the current time.

The Space Segment

- There are typically 32 satellites in orbit; 24 are operational, and the others are used as backups.
- Each satellite is approximately 17 feet across and weighs approximately 2000 lb.
- The satellites are in orbit **10,900 nm (approximately 20,200 km)** above the earth; this orbit provides optimum ground coverage with the least number of satellites.
- Each satellite is installed with **four atomic clocks** that are extremely accurate, typically maintaining accuracy within three nanoseconds (3 10^{-9} seconds) per day. (Four clocks are installed for backup purposes in the event of failure).
- The satellites are powered by the sun’s energy via solar panels; nickel cadmium batteries provide electrical power backup.
- Each satellite orbits the earth twice per day at an inclination angle of 55° with respect to the equatorial plane; there are six defined orbits, each containing four satellites.
- The net result of this orbital pattern is that a minimum of five satellites should be in view to a receiver located almost anywhere on the earth’s surface.
- Satellites have a finite operational life, typically **five to ten years**.

GPS Space Segment

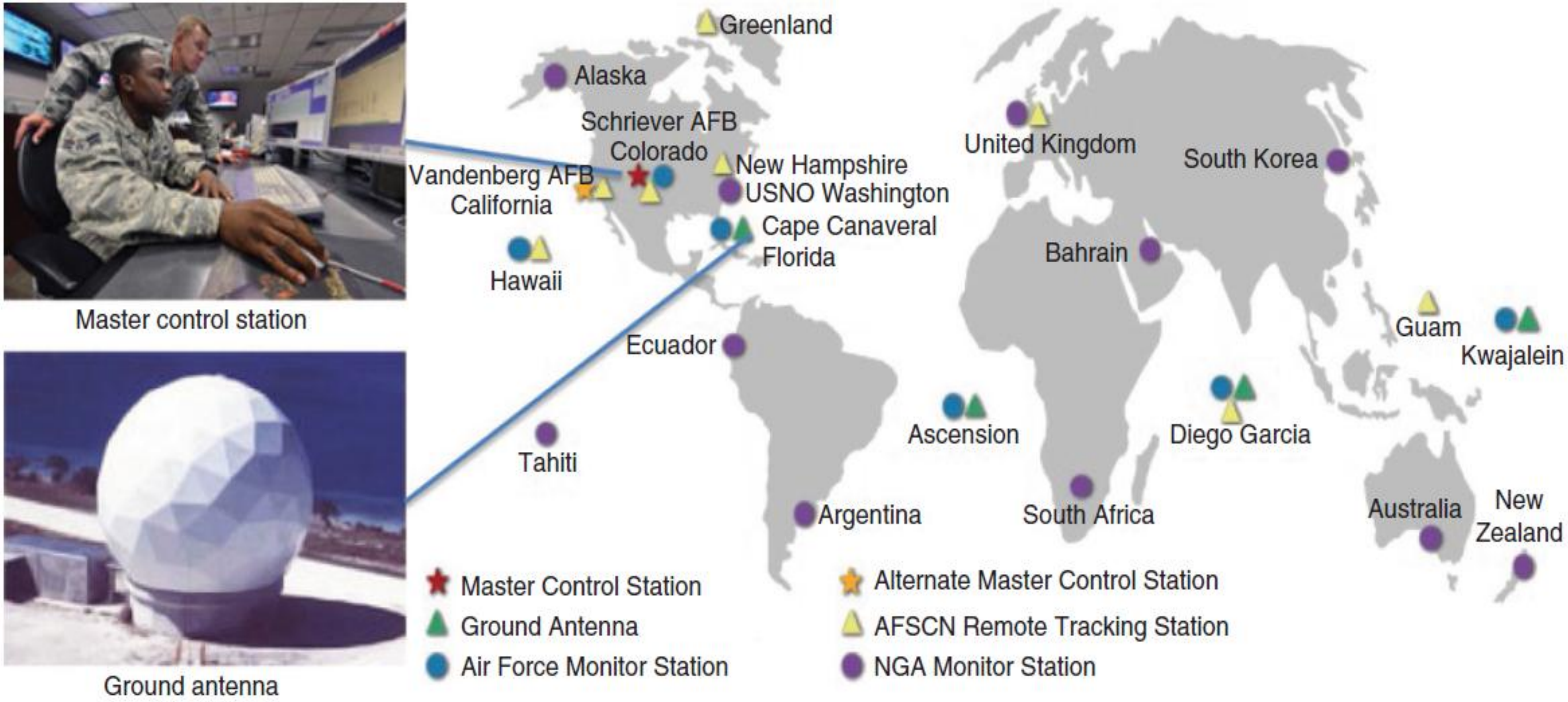
Typical navigation satellite



The Control Segment

- The GPS control segment comprises:
  - **A Master Control Station**
  - **A Back-up Control Station**
  - **5 Monitoring Stations**
- The control segment comprises one master control station (MCS) located at Schriever (formerly Falcon) Air Force Base in Colorado Springs, USA; five monitoring stations (located in Colorado Springs, Hawaii, Kwajalein, Diego Garcia and Ascension Island); and three ground antennas (located on Ascension Island, Diego Garcia and Kwajalein).
- The locations of the monitoring stations provide ground visibility for each satellite.
- Although each satellite's clock is very accurate, the relative timing between satellites gradually drifts over time.
- The individual clocks are monitored and synchronized mathematically relative to Coordinated Universal Time (UTC) by the master station. (UTC is the basis for the worldwide system of time).

Control Segment of the GPS System

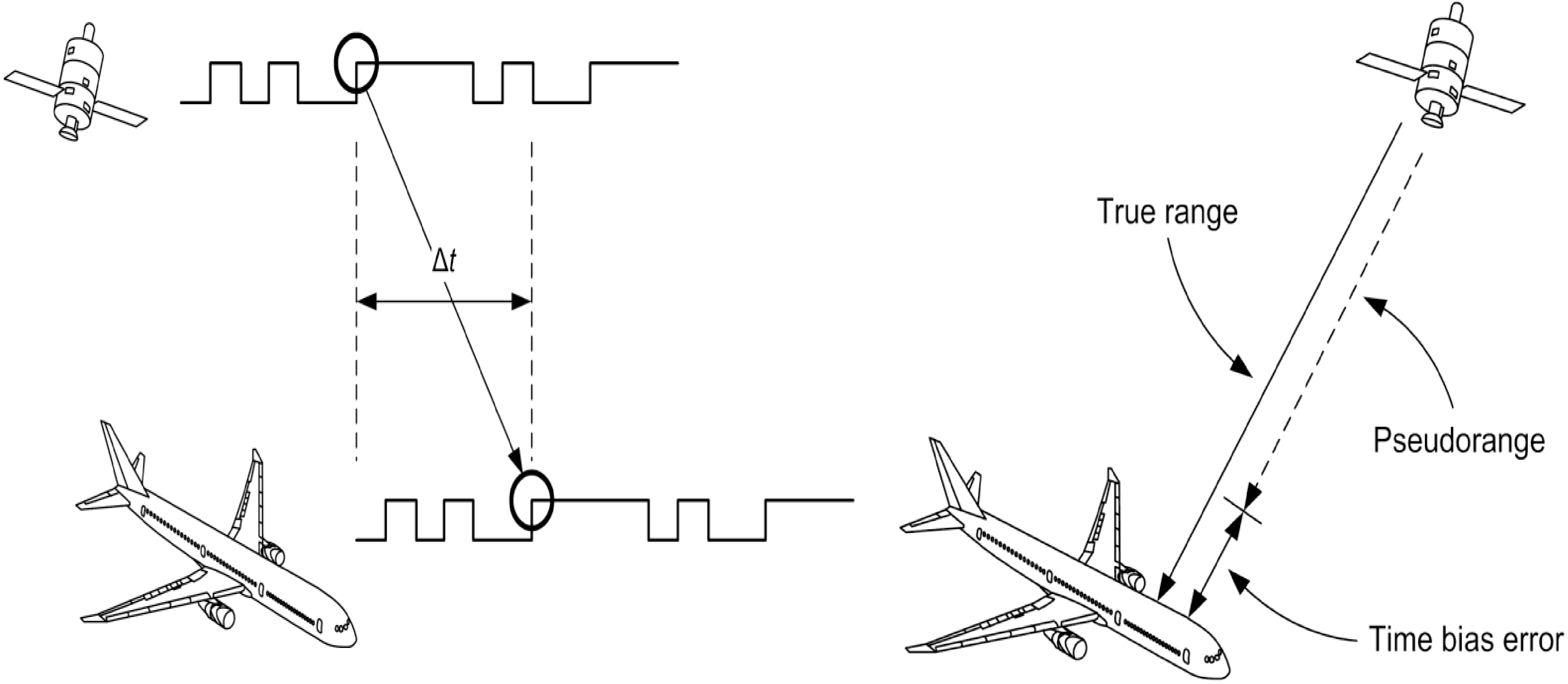


The User Segment

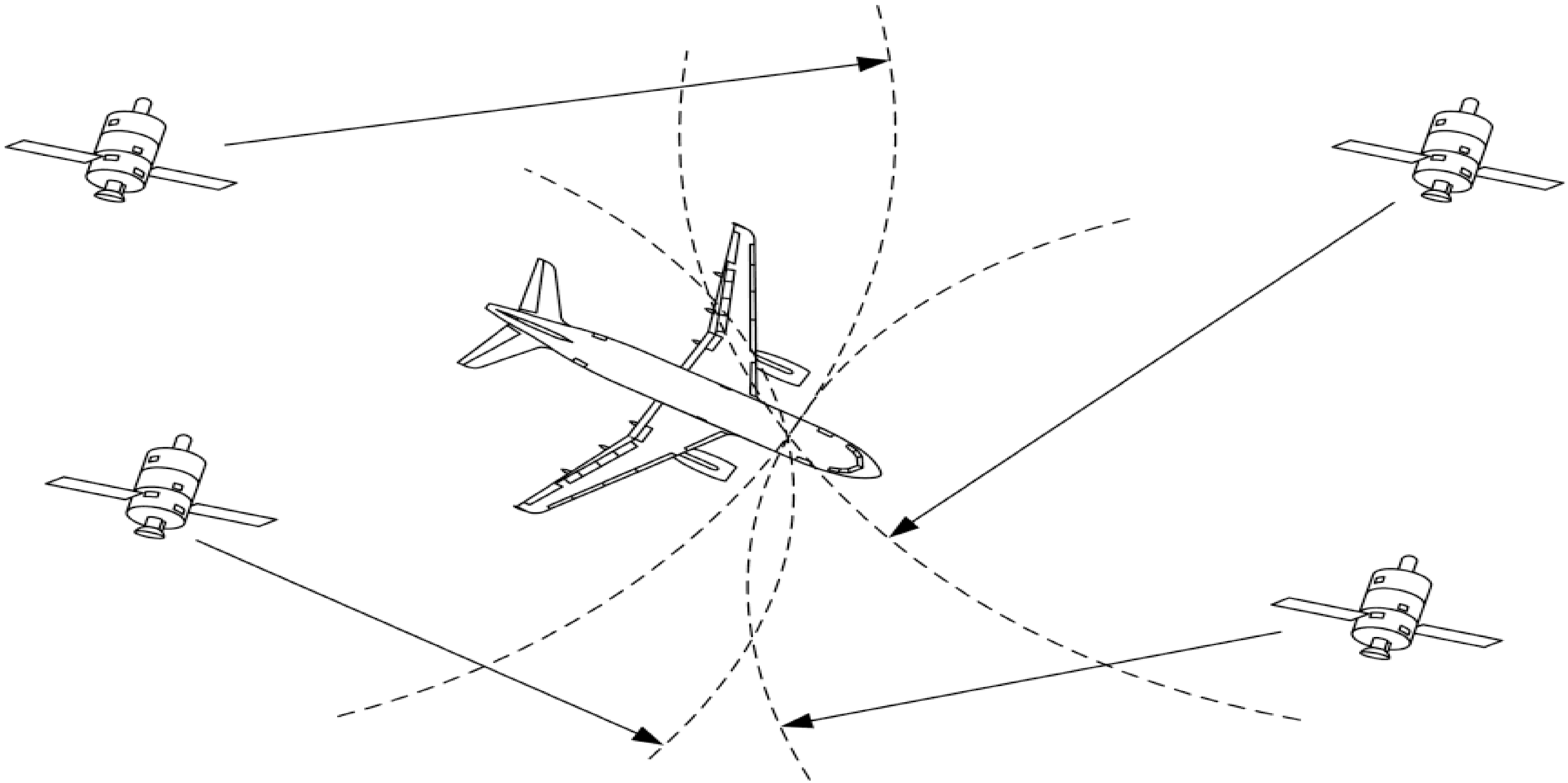
- GPS installed on an aircraft comprises two receivers and two antennas located in a forward position on the top of the fuselage.
- Antennas are typically flat devices, 7 x 5 x 0.75", with a single coaxial connector.
- Satellites that are less than 5° from the horizon are rejected as an inherent feature of the antenna’s design.
- Other design features include the ability to reject signals that are reflected, e.g. from the sea, by rejecting incorrectly polarized signals.
- The antennas receive signals directly from whichever GPS satellites are visible, i.e. within line of sight.
- The receiver and satellite generate identical pulse coded signals at precisely the same time; these signals are compared in the receiver to provide the basis of time delay (Δt) measurements.
- When the time delay from the satellite has been measured, it is compared with the known position and orbit of the satellite.
- This calculation provides a first **Line of Position** (LOP).

Location of GPS Antennas

Illustration Pulse-coded Signals of Pseudorange



Pseudorange and Position Fixing with Four Satellites



GPS Signals

- Each satellite transmits low power (20–50 watt) signals on two carrier frequencies: **L1 (1575.42 MHz) and L2 (1227.60 MHz).**
- Two carrier waves are transmitted so that the effects of refraction through the ionosphere can be compared between the two signals and corrections applied.
- These carrier frequencies are modulated with **complex digital codes** that appear like random electrical noise; these are called **pseudorandom codes**, and they are a fundamental part of a GPS.
- There are three sets of data to be modulated on the L1 and L2 carrier waves:
  - Course acquisition (C/A) code
  - Precise (or protected) P-code
  - Navigation/system data.

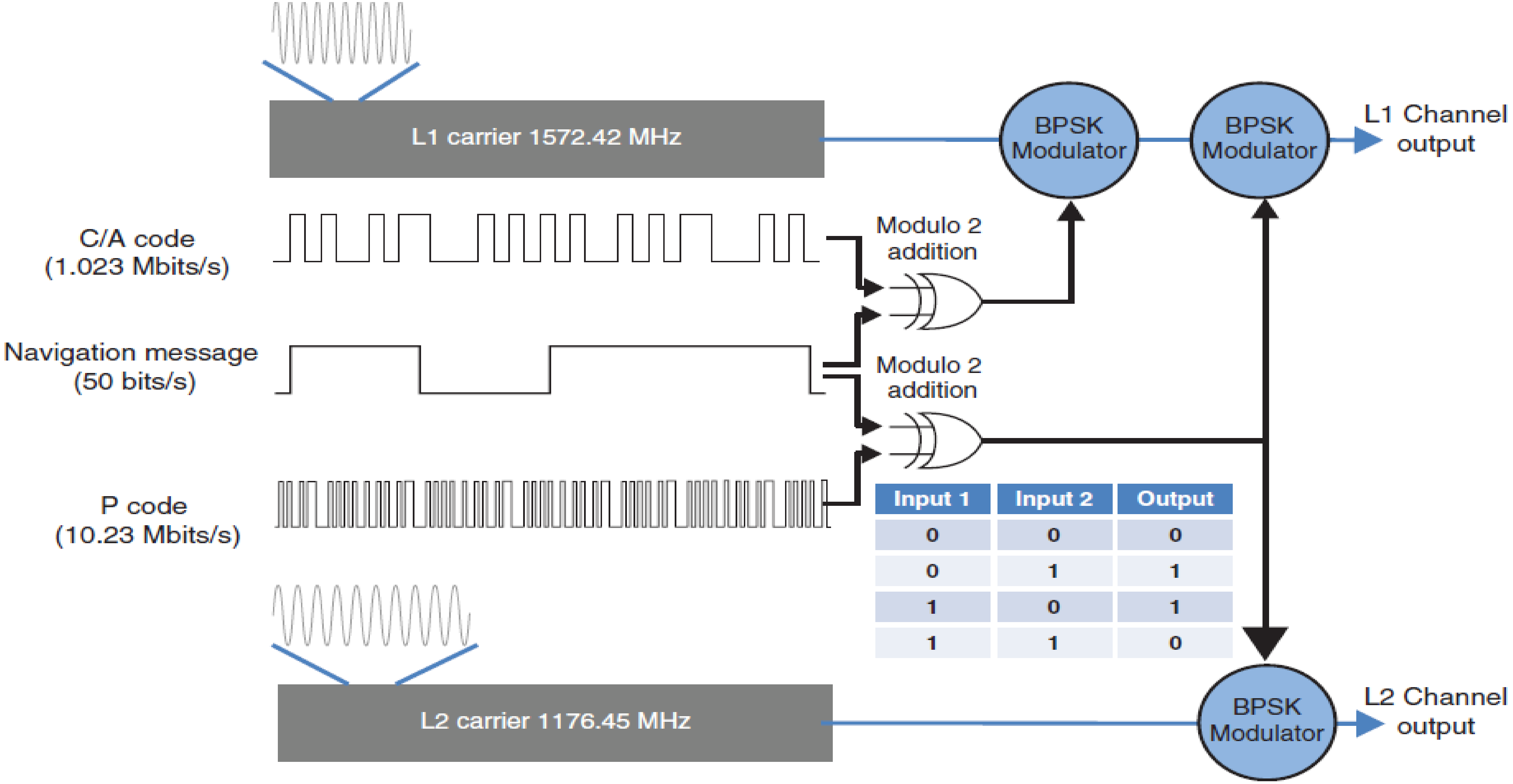
GPS Signals (2)

- **The coarse acquisition (C/A)** code is a pseudorandom string of digital data used primarily by commercial GPS receivers to determine the range of the transmitting satellite. The C/A code modulates the carrier wave at **1.023 MHz** and repeats every 1 ms.
- **The P-code** (not available to civilian users) is modulated on both the L1 and L2 carriers at a frequency of 10.23 MHz. The P-code can be further encrypted as a Y-code to provide a high level of security for military users.
- **Data** is exchanged between each satellite and the monitoring stations via uplink and downlink frequencies in **the S-band (2227.5 and 1783.74 MHz** respectively).

Note:

- **Pseudorandom Noise (PRN)** codes allow all satellites to transmit at the same frequency. Each satellite uses a unique PRN code; these carry the navigation message and are used for acquisition, tracking and ranging.

Modulation of the L1 and L2 Channels



Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	0

GNSS Operation

- GNSS has various levels of operation depending on how many satellites are in view.
- **Three satellites** provide a **two-dimensional position fix**; **four satellites** or more are desirable for optimum navigation performance.
- The receiver seeks out at least four satellites by monitoring their signal transmissions; this acquisition process takes about 15–45 seconds.
- To speed up the navigation process, the receiver can obtain an initial position fix from **the inertial reference system**; this allows the receiver to search for satellites that should be in view.
- In the event of poor satellite coverage for defined periods (typically less than 30 seconds), the system uses other **navigation sensor inputs** to enter into a **dead reckoning mode**.
- For prolonged periods of poor satellite reception, the system re-enters the acquisition mode.

GNSS Integration

- GNSS equipment can be used in isolation or with other avionic systems to provide differing levels of operation.
- For example, in General Aviation (GA), GNSS receivers are often integrated with **ILS–VOR and VHF communication systems**.
- This example is a self-contained, panel-mounted device.
- Graphics are used to provide a multifunction type display; text is displayed on the screen for selected frequencies, distances, bearings, etc.

Satellite Page on Cockpit Display

European GNSS

- Galileo is the European system, intended to be compatible with, but more advanced than, GPS or GLONASS.
- The system is based on **24 operational satellites plus 6 in-orbit spares**, in a higher **(23,000 km)** orbit; the satellites form **three orbital planes**, each comprising **10 satellites.**
- With this higher orbit is an increased time to circle the earth: **14 hours**.
- The ground system comprises **two control centers**, **five monitoring** and **control stations** and **five uplink stations**.
- Initial services will be made available by the end of 2016, with system completion scheduled for 2020.
- As a further feature, Galileo is providing a global Search and Rescue (SAR) function based on the operational Cospas-Sarsat system.
- The European Geostationary Navigations Overlay Service (EGNOS) is the first phase of Galileo.
- EGNOS utilizes a network of ground stations and three geostationary satellites to provide increased accuracy, integrity and reliability of any global satellite navigation system.

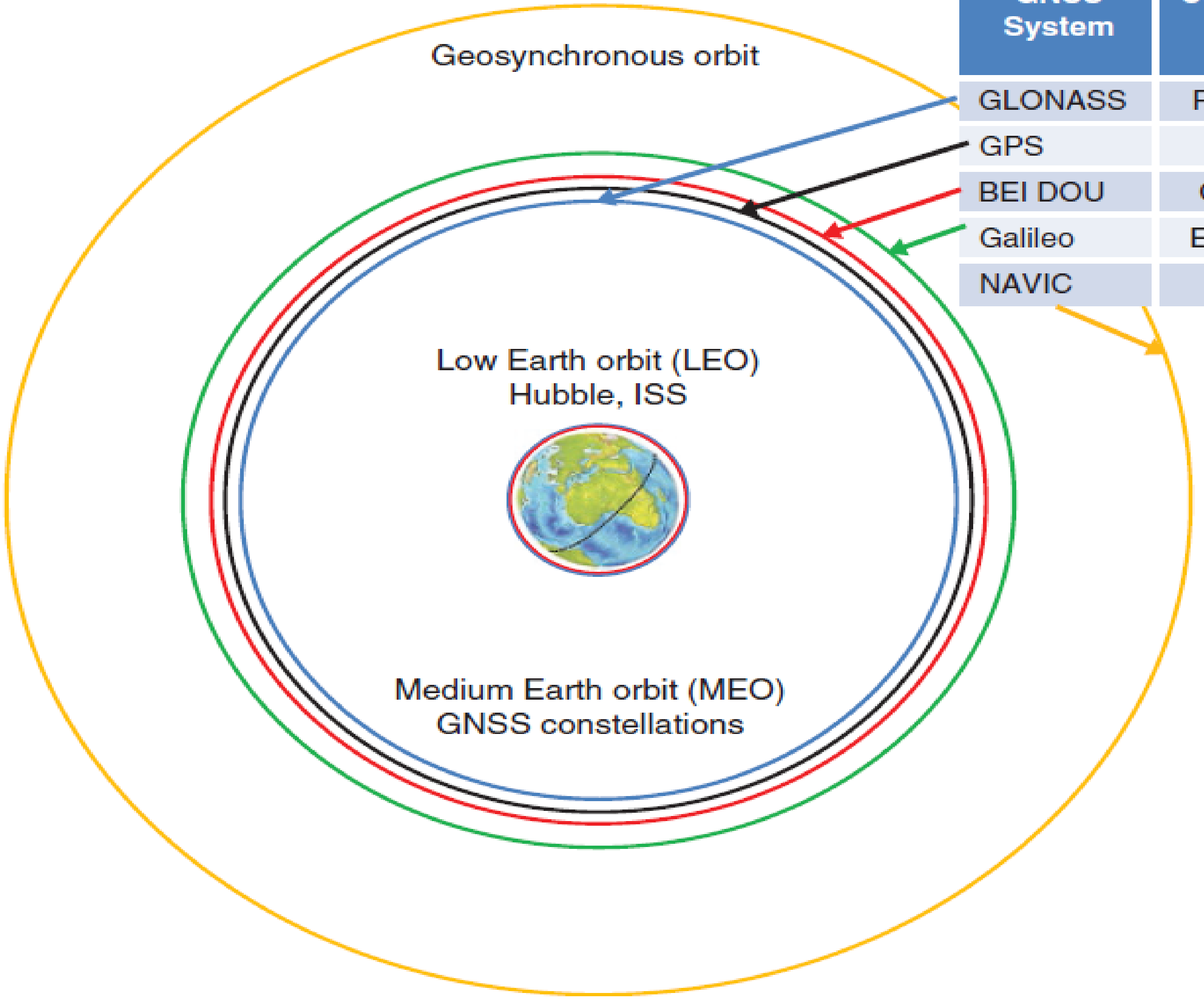
Russian GNSS (GLONASS)

- The Russian Global Navigation Satellite System (GLONASS) is based on a constellation of active satellites similar to GPS Navstar.
- The planned space segment is:
  - A constellation of 24 satellites
  - Arranged with 8 satellites in 3 orbital planes
  - Satellites are identified by a slot number, which defines the orbital plane (1-8, 9- 16,17-24) and their locations within the plane
  - The three orbital planes are separated by 120° of longitude at the equator and the satellites within the same orbit plane by 45° of arc.
  - GLONASS orbits are roughly circular with an inclination of about 64.8°
  - The orbit is at 19 000 km with a period of 11 hrs 15 m 44 s.
- The ground control segment of GLONASS is entirely located in Russia.

Other GNSS

- **Japan**, **China** and **India** are planning and implementing their own satellite navigation systems; other nations are either joining or forming partnerships.
- Some novel ideas include optimizing orbits such that the satellite(s) remain visible over certain areas of the globe for longer periods to obtain maximum usage.
- Estimates vary, but it is conceivable that over 100 navigation satellites could be in orbit over the next 20 years.
- Since the original global navigation systems were established, there remains a political debate about the deployment of additional systems.
- This debate is fueled by a number of factors, e.g. national security aspects (remember that GPS was originally established as a US military asset).
- From the commercial aviation perspective, if there are numerous systems in place, there is the added ‘complication’ of what equipment will be approved in each and every nation.

The Various Operational GNSS Constellations



GNSS System	Country	Orbital period (sidereal days)	Orbital radius (km)
GLONASS	Russia	8/17	25 500
GPS	USA	1/2	26 600
BEI DOU	China	9/17	27 600
Galileo	Europe	10/17	29 600
NAVIC	India	1	42 100

GNSS Applications

- GNSS with suitable augmentation will provide for:
  - Accurate enroute navigation including area navigation capabilities
  - Terminal area routing
  - Precision approaches
- The Automatic Dependent Surveillance Broadcast (ADS-B) is also using GNSS. The system digitises the position information derived from the GNSS and broadcasts it as part of a data stream, which includes:
  - Aircraft identification/flight number
  - Aircraft type
  - Altitude
  - Speed
  - Heading
  - Flight condition (climbing, turning levels, etc.)

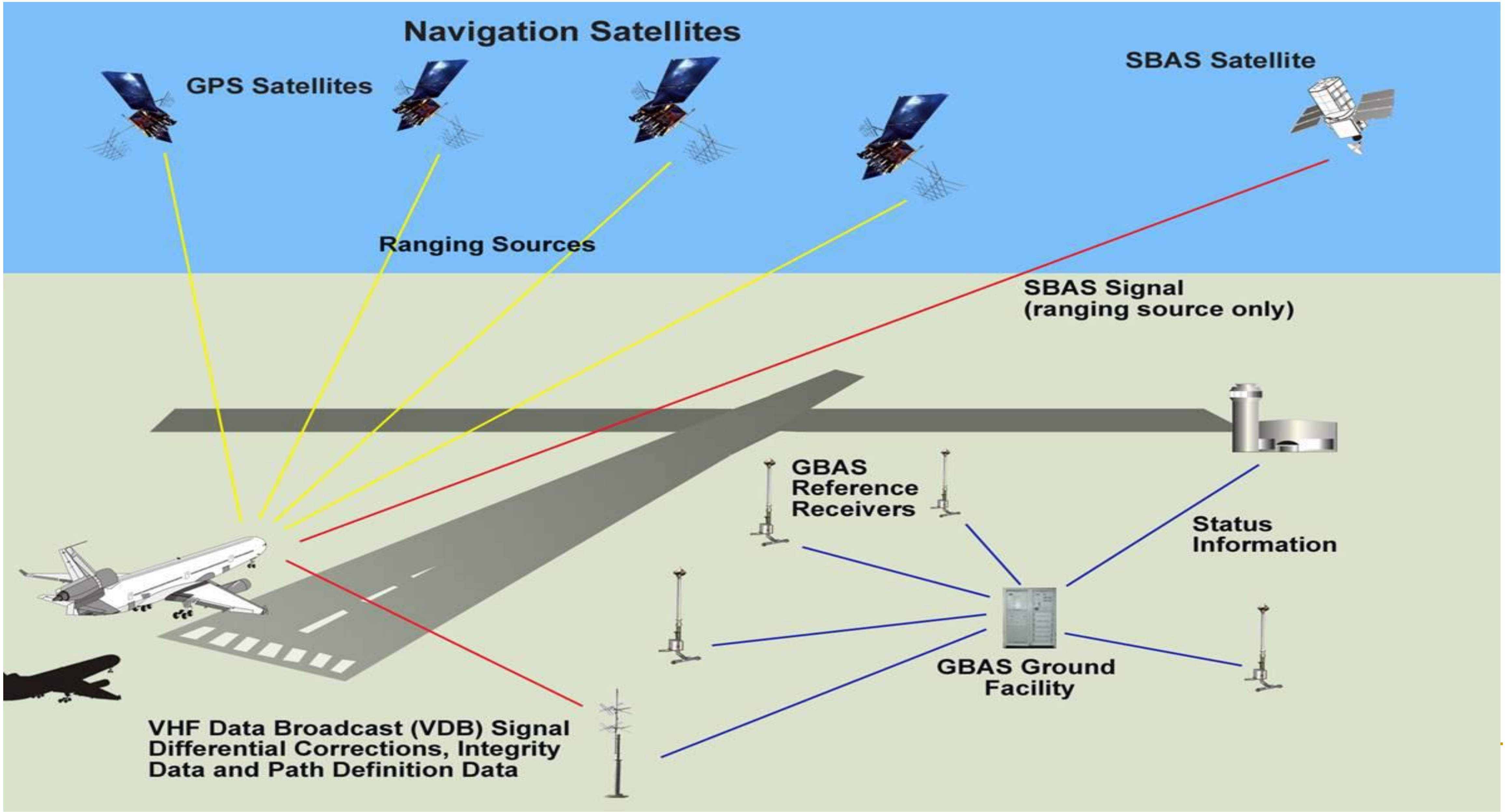
GNSS Augmentation

- GNSS constellations require augmentation systems to meet ICAO performance requirements for **en route, terminal, approach and landings**.
- A combination of on-board avionics and (where available) external references are implemented via:
  - **Aircraft-Based Augmentation System (ABAS)**
  - **Satellite-Based Augmentation System (SBAS)**
  - **Ground-Based Augmentation System (GBAS)**
- **ABAS** is the on-board avionics implementation that processes GNSS signals to achieve the accuracy and integrity required to support **en route, terminal and non-precision approach (NPA)** operations.
- **SBAS** uses a network of ground reference stations and **Geostationary Earth Orbit (GEO)** satellites to augment en route navigation and approaches with vertical guidance.
- **GBAS** uses airport monitoring stations to process signals from GNSS constellations and broadcast corrections and approach path data to **support precision approach and landing operations.**

Ground Based Augmentation System (GBAS)

- The current core constellation is unable to provide accuracy, availability, continuity and integrity to achieve precision approach.
- GBAS uses the concept of differential corrections to augment satellites signal in order to meet these requirements.
- GBAS provides augmentation to the core constellations to enable **precision approach up to Category III.**
- GBAS works based on three segments: **satellites constellation, ground station and aircraft receiver.**
- GBAS ground station is formed by **reference receivers** with their antennas installed in precisely surveyed points.
- The GBAS approach indication to the pilot is similar to the course and glide path indications of ILS.

GBAS Architecture



Benefits of GBAS

Comparing to other precision approach systems, GBAS presents lots of benefits:

- Reduction of critical and sensitive areas;
- Curved approach;
- Positioning service;
- Provision of service in several runways in the same airport;
- Provision of several approach glide angles and displaced threshold;
- Guided missed approach; and
- Adjacent airports use.

GBAS Basic Technical Information

- GBAS is intended to support all types of **approach, landing, departure and surface operations** and may support en-route and terminal operations.
- The GBAS ground station performs the following functions:
  - Provide locally relevant pseudo-range corrections;
  - Provide GBAS-related data;
  - Provide final approach segment data when supporting precision approach;
  - Provide ranging source availability data; and
  - Provide integrity monitoring for GNSS ranging sources.

GNSS – The Future

- The long-term (circa 10 years) intention of the aviation community is to rationalize the air traffic management through increased use of GNSS; this will be realized with the various augmentation.
- There are programmes in place to eventually replace ADF and VOR navigation aids.
- DME navigation aids will be retained for a longer period to optimize the existing network.
- Automatic approach and landing with GNSS will use ILS/MLS to mitigate for satellite outage and/or disruption.
- With increased dependence on GNSS, the impact of any disruption is significant.

Thanks!

ありがとうArigatō

谢谢谢 Xièxiè!

감사해요 Gamsahaeyo

Technology changes but communication lasts.