# Introduction to GPS

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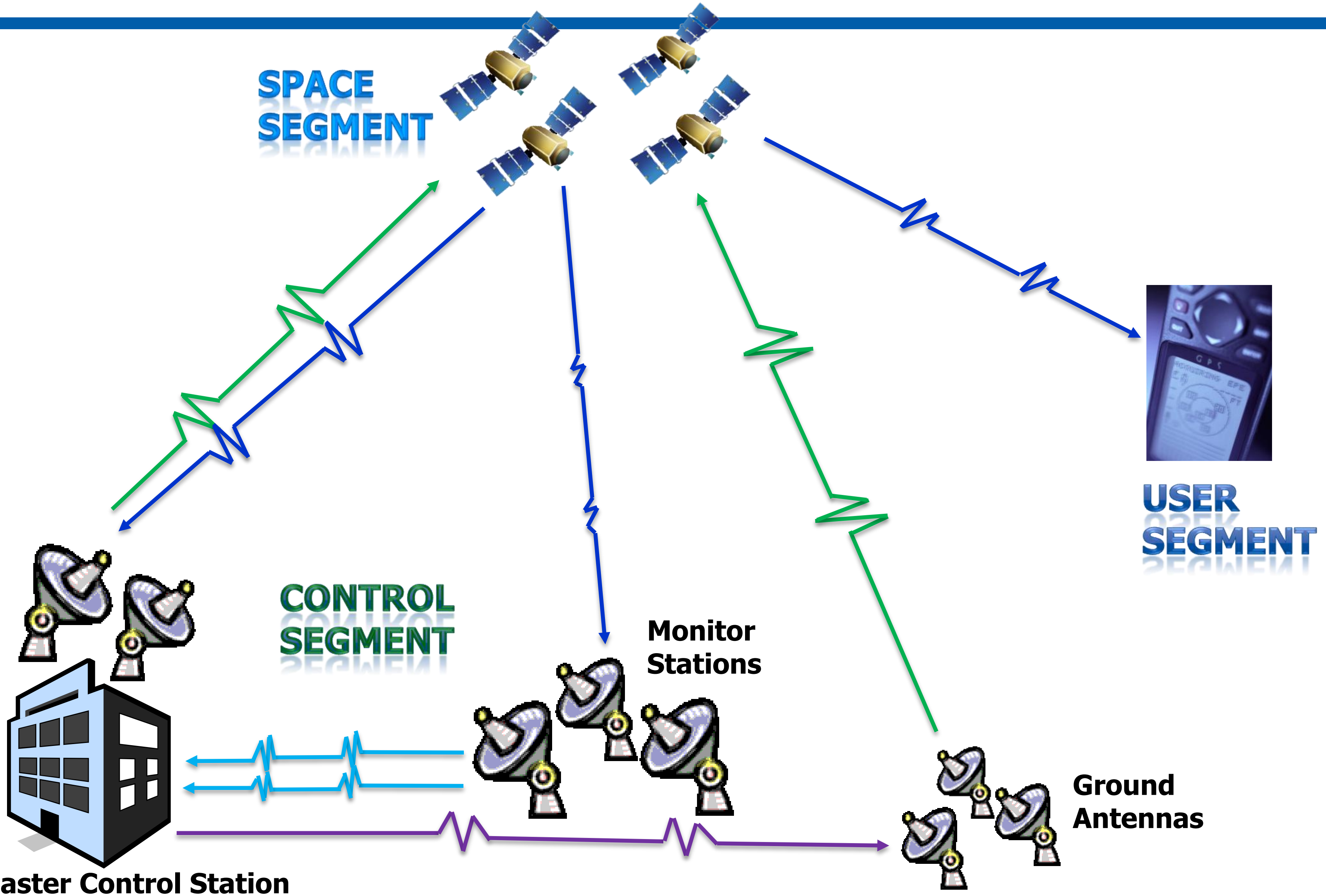
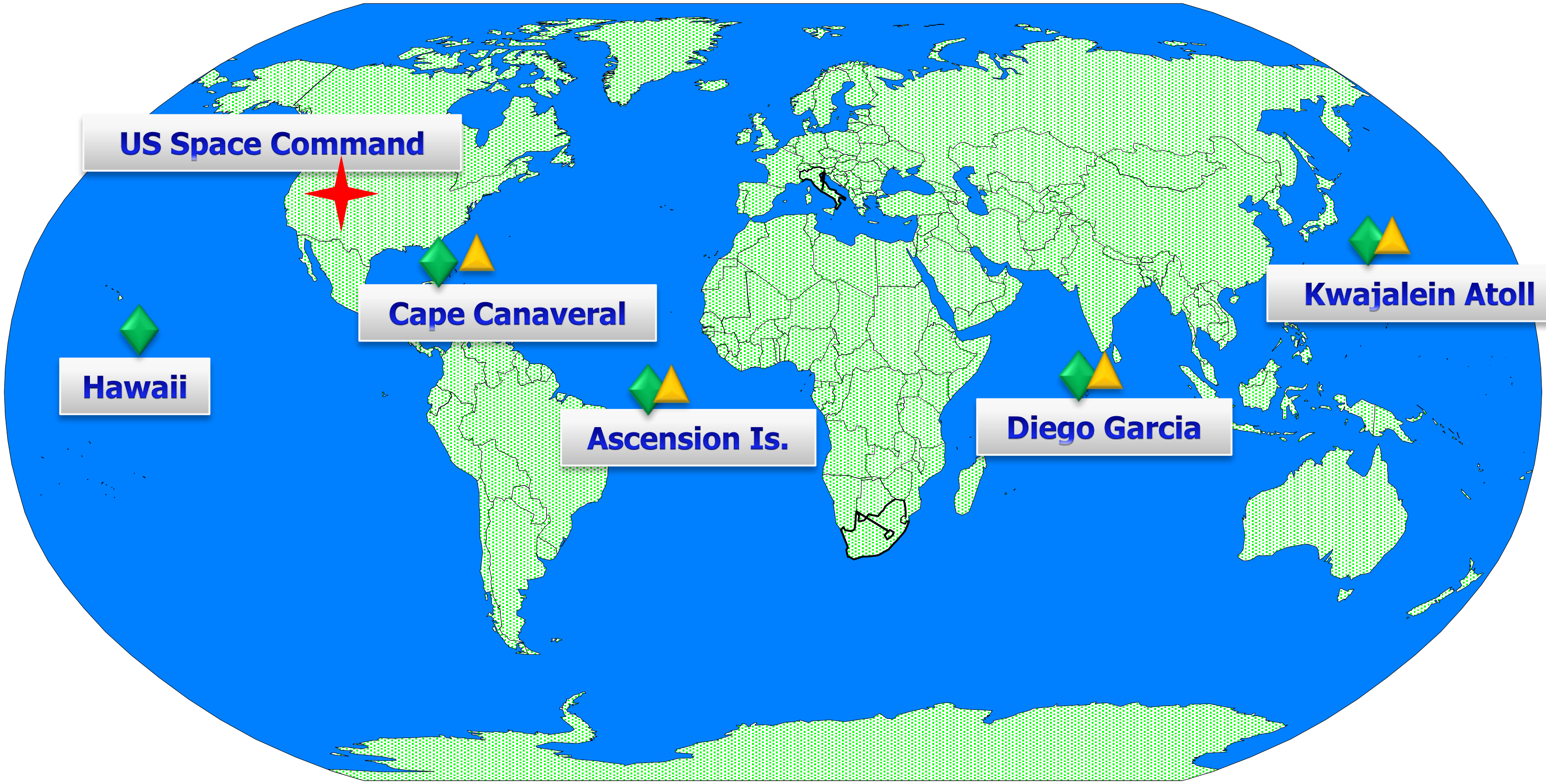
# History of GPS (Global Positioning System)

- Feasibility studies begun in 1960's
- Defense Navigation Satellite System (DNSS) formed in 1969
- Pentagon appropriates funding in 1973
- First 4 satellites launched in 1978
- $24^{th}$ satellite launched; IOC in 1993
- Fully operational in April, 1995
- Selective Availability (SA) turned off in 2000

# Three Segments of the GPS



# Control Segment




**Master Control Station**

- Resource allocation/scheduling
- Navigation message generation
- Satellite health
- Constellation steering
- Status/performance evaluation

**Monitor Station**

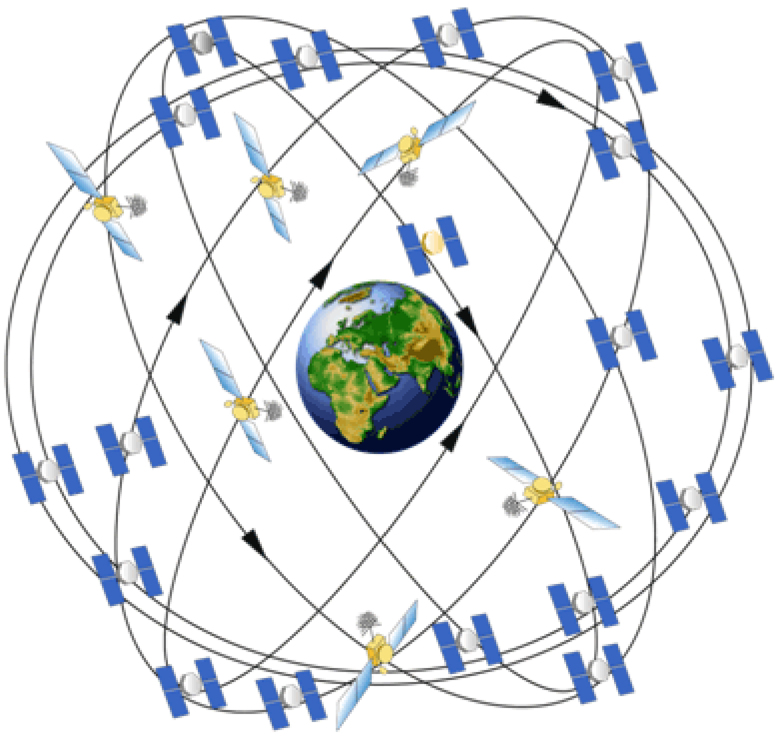
- Signal tracking
- Range and carrier measurement
- Atmospheric data collection
- Collect decoded navigation data

**Ground Antenna**

- SV command transmission
- SV processor load transmission
- SV navigation message upload
- Collect SV telemetry

# Space Segment

- Number of satellite vehicles (SVs)
  - Minimum: 24
  - Maximum: 32
- Six orbital planes
  - Inclined 55$^{o}$ with respect to equator
  - Orbits separated by 60$^{o}$
- 20,200 km elevation above Earth
- Orbital period of 11 hr 55 min
- 5 to 8 satellites visible from any point on Earth
- Broadcast three signals on two frequencies
  - Coarse/Acquisition (C/A) signal for civilian use
    - For Standard Positioning Service (SPS)
    - Transmit at L1 @ 1575.42 MHz
  - Precision (or Y-encrypted) (P(Y)) signal for military use
    - For Precise Positioning Service (PPS)
    - Transmit at L1 @ 1575.42 MHz and L2 @ 1227.60 MHz



**GPS Constellation**

**Today we have 31 GPS satellites operational**

# Satellite Vehicle (SV) Block Development

- Block I, II, IIA
  - 38 SVs launched successfully from1978 to 1997
- Block IIR: Replenishment SV
  - 12 SVs launched from1997 to 2004
  - Better atomic frequency standards
  - Better accuracy and enhanced autonomy
- Block IIR-M: Modernized SV
  - 8 SVs launched from 2005 to 2009
  - Modernized hardware (antenna panel, L-band system, etc)
  - Add three new (modernized) signals
    - L1 M signal and L2 M signal for military use
    - L2C signal for civilian use
- Block IIF: Follow-on SV
  - 12 SVs schedule with first one launched in 2010
  - Add another new signal L5 @ 1176.45 MHz
- Block IIIA: Next Generation SV (2014)
  - Add another new signal L1C


Block II/IIA


Block IIR/IIR-M


Block IIF

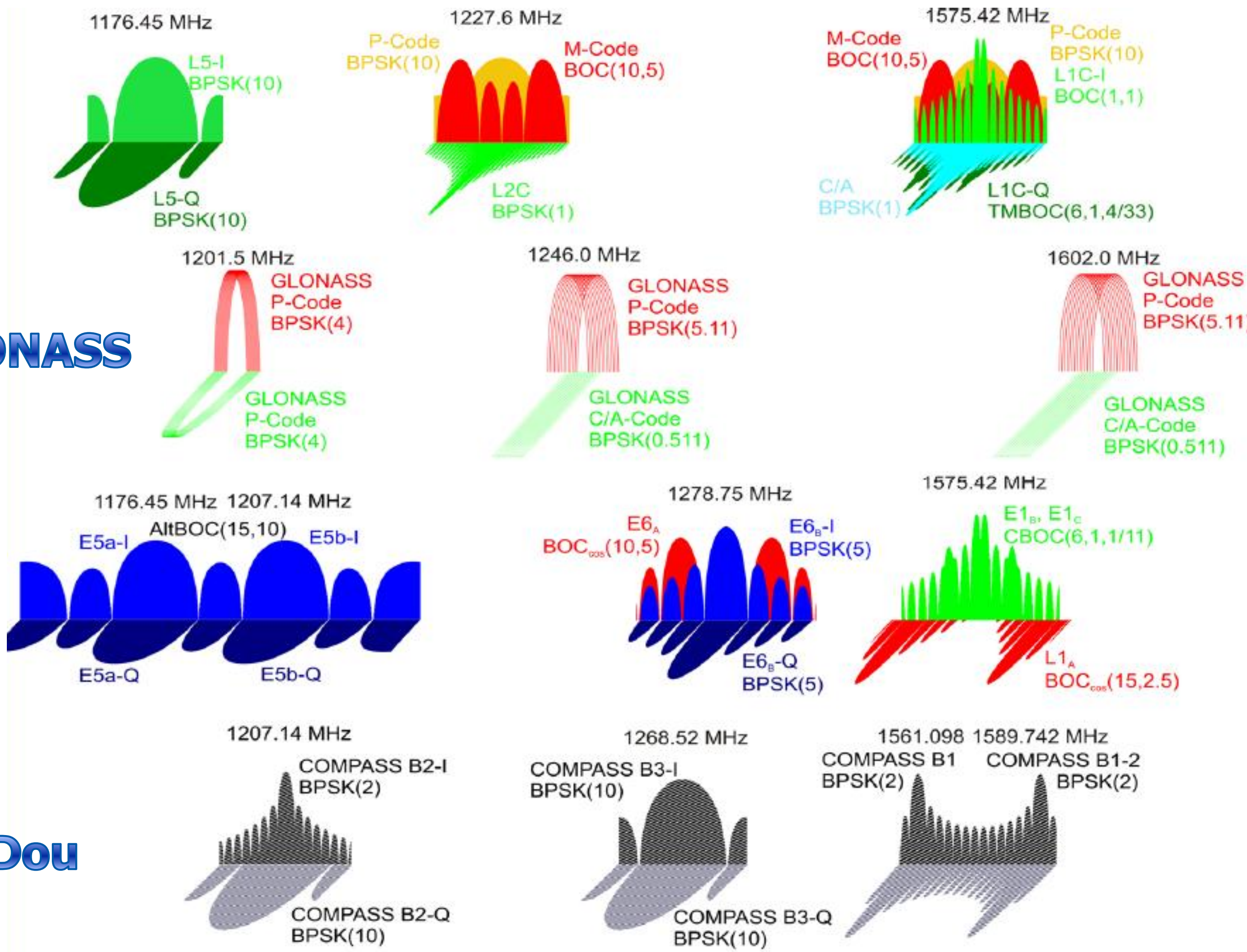
# US and Other Satellite Navigation Systems

**US GPS**

**Russian GLONASS**

**European GALILEO**

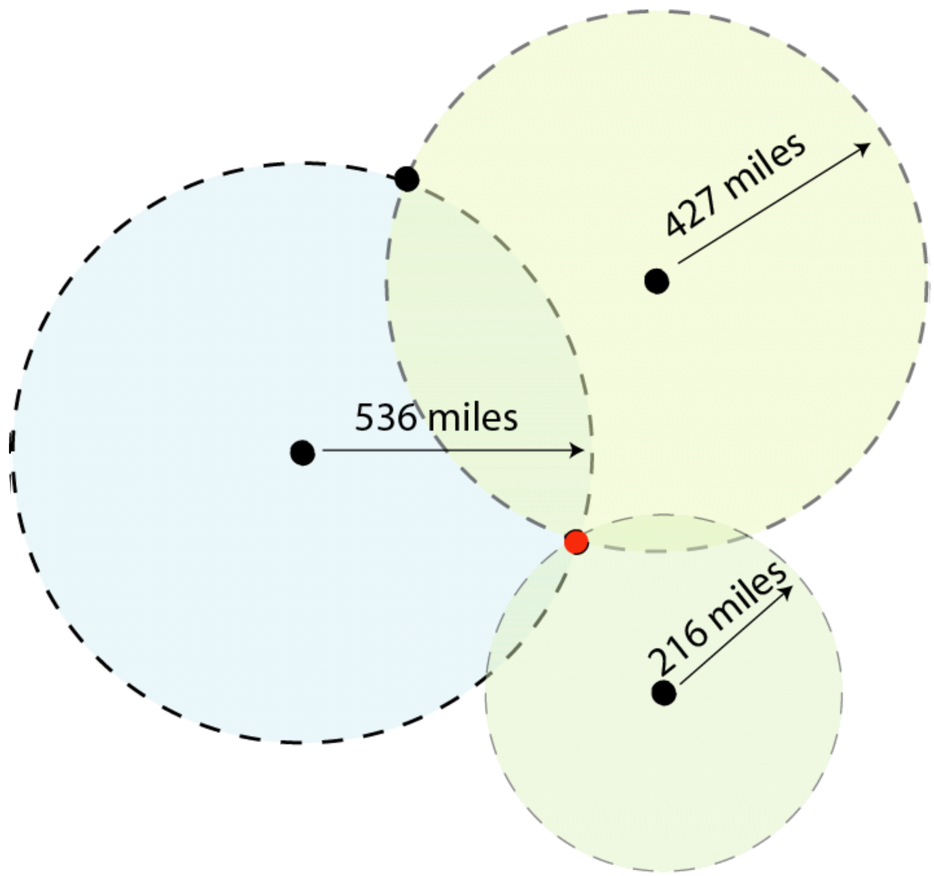
**Chinese BeiDou**




From Gunter Hein, FAF Munich

# Basic Concept of GPS - Triangulation

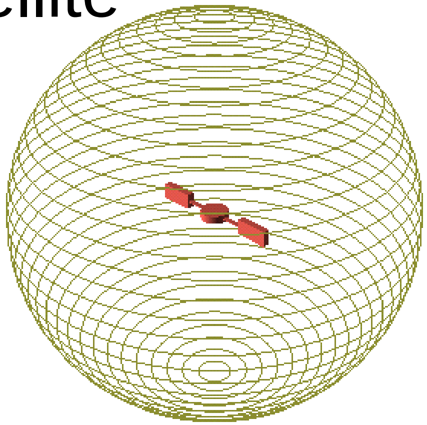
- In 2-D space, we can determine the position by distance measurements to two known locations with prior knowledge



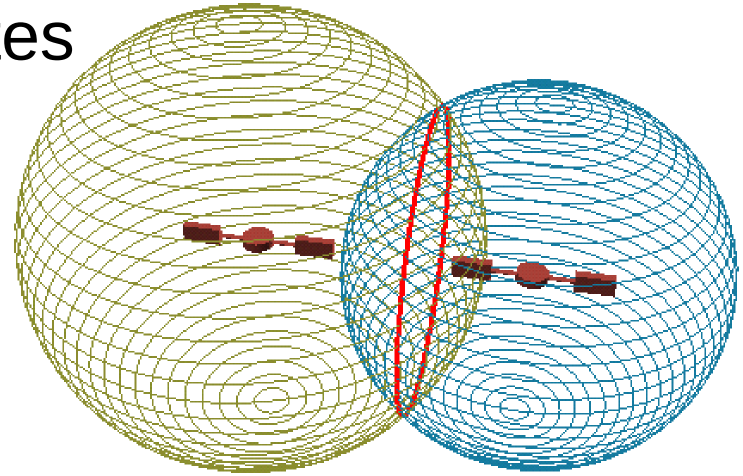

- Without prior knowledge, need three measurements

# 3-D Trilateration

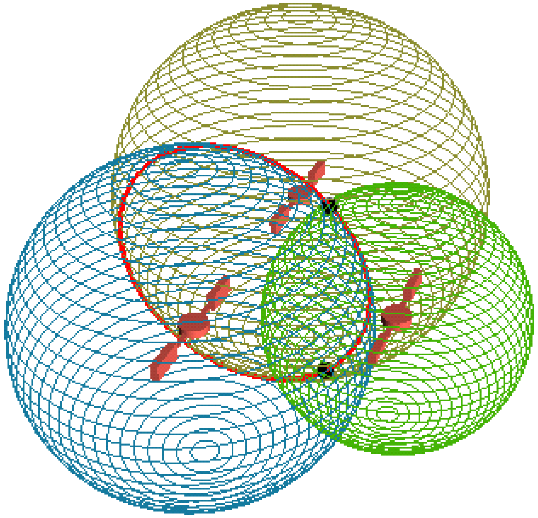
1 Satellite

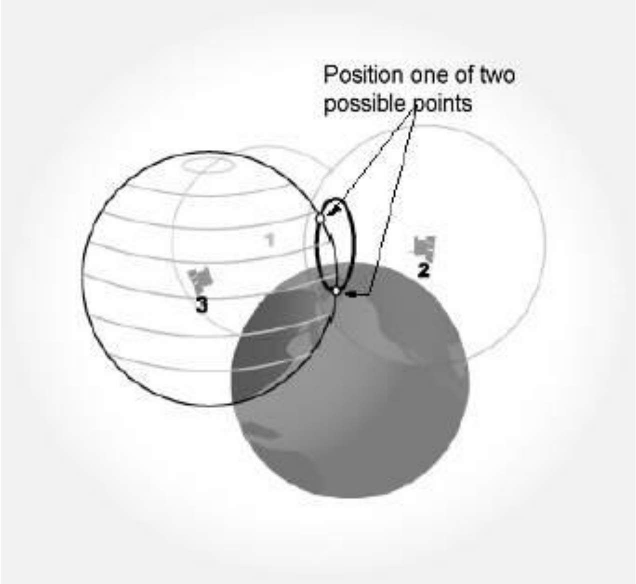


2 Satellites

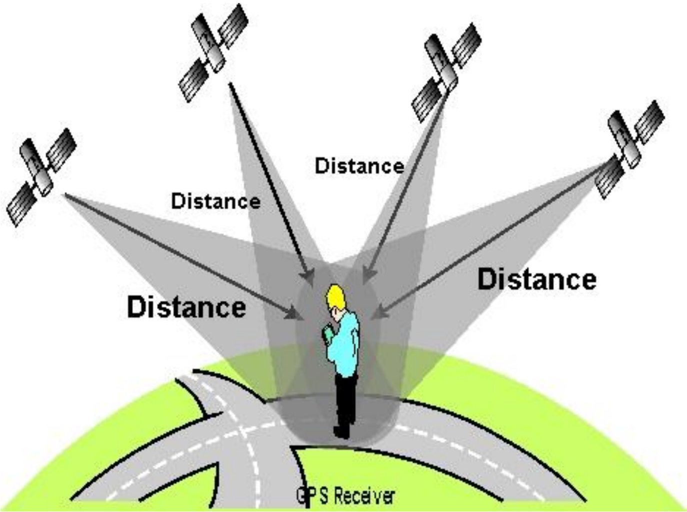


3 Satellites





# Basic Concept of GPS




- How does one determine his position
  - Know the satellite location
  - Know when the satellite sends the signal
  - Know when the user receives the signal
  - Calculate satellite to user distance
    - Distance = speed of light x signal travel time from satellite to user
  - 3-D Trilateration will provide the user position
- Very SIMPLE in concept, but very complicated in details

# Speed of Light

**Signal travel time = user receive time - satellite transmit time**

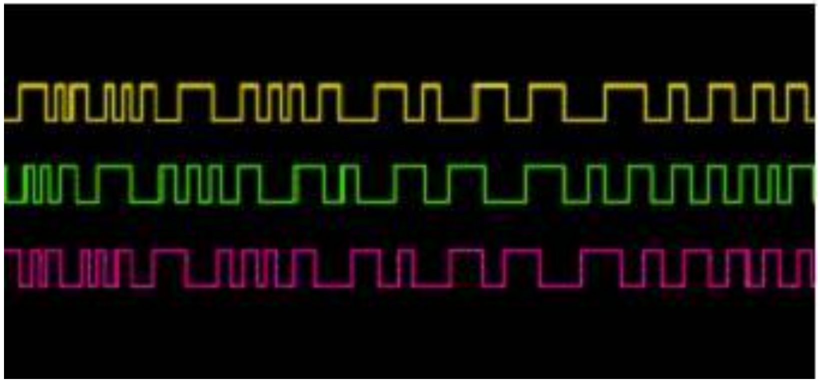
- Speed of Light = **299,792,458** meters per second
- Speed of Sound = 340 meters per second
- Reverse Engineering
  - 1 meter position accuracy ≈ 3.3 nano-second timing accuracy
- As a byproduct of getting accurate position, the user also get accurate time

# GPS Signals

- Pseudorandom code
  - Time
  - Satellite Number

- Pulse rate
  - Civilian C/A code @ 1 Mbps
  - Military P(Y) code @ 10 Mbps

- Navigation Message, 50 bps
  - Ephemeris data
    - Satellite's own precise location
    - 17 parameters
  - Clock data
    - Satellite's own clock offset error
  - Almanac data
    - Coarse locations of all satellites
    - 10 parameters
    - Help tracking of new satellite

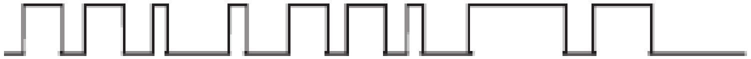


Physically the signal is just a complicated digital code, or in other words, a complicated sequence of "on" and "off" pulses.

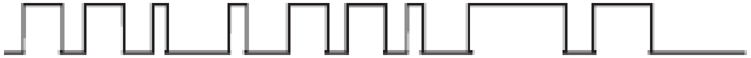
# Time Difference

- The GPS receiver compares the time a signal was transmitted by a satellite to the time it was received. The time difference tells the GPS receiver how far away the satellite is.

Satellite transmits at 11:00:00.00



GPS unit receives at 11:00:00.07



- If it took 0.07 second for the signal to travel from satellite to receiver, we can calculate the distance as

  0.07 seconds **x** 299,792,458 meters per second = 20,985 km = 13,040 miles

- What if we measure the time difference as 0.07001 seconds
  - 10 micro-second time measurement error
  - **That is a 1.86 mile error**

# Four Distance Measurements

- Three unknown in the position variable (x, y, z)
- Theoretically, we only need three distance measurements
  - 3 equations to figure out 3 unknowns

- Distance measurements require accurate timing at both satellite and user
  - GPS satellite timing is stable because it has four atomic clocks ($$$)
  - GPS satellite timing is accurate because constant time offset is corrected by MCS

  - User/receiver timing is neither stable nor accurate
  - Fortunately, it can be modeled as one more unknown value in the calculation

- Four unknowns: $(x, y, z, \Delta t_u)$
  - In fact, $\Delta t_u$ not only captures receiver clock error but all other common error

- Need minimum of <u>FOUR</u> distance measurements to resolve four unknowns

# What if we have more than 4 measurements

- We have an over-determined system of equations

- Solution: Least Squares
  - Minimize the sum of squares of the errors
  - First developed by Carl Friedrich Gauss in 1795 at the age of 18 to predict the future location of asteroid (This was before linear algebra was invented)

$x = 1$, $x = 2$ → Minimize $(x-1)^2+(x-2)^2$ → $x = 1.5$

- For GPS application, we need to solve the nonlinear least square problem

$$\underset{x,y,z,t}{\text{minimize}} \sum_{i=1}^{\#\text{ of SVs}} \left(\underbrace{\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}}_{\text{Distance from } i^{th} \text{ Satellite to Receiver}} + \overbrace{ct}^{\text{Receiver Clock Error}} - \rho_i\right)^2$$

Receiver Clock Error: $ct$

Distance from $i^{th}$ Satellite to Receiver: $\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}$

Distance Measurement to the ith Satellite: $\rho_i$

- Solved numerically by Newton's method
  - Iterative method
  - Require calculation of the Gradient and Hessian
  - Quadratic convergence rate
  - Typically obtain accurate solution in 5--10 iterations

# GPS Position Error

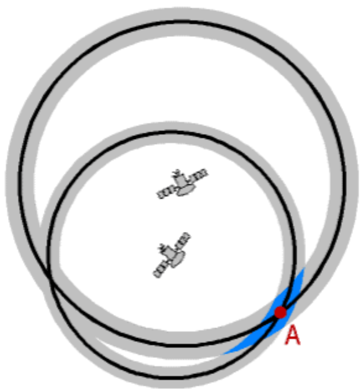
**Position Error ≈ PDOP x Distance Error**

- PDOP – Positional Dilution of Precision
  - A function of number of satellites and geometry
  - A PDOP of < 2 is excellent
  - A PDOP of 2--4 is good
  - A PDOP of >4 is poor

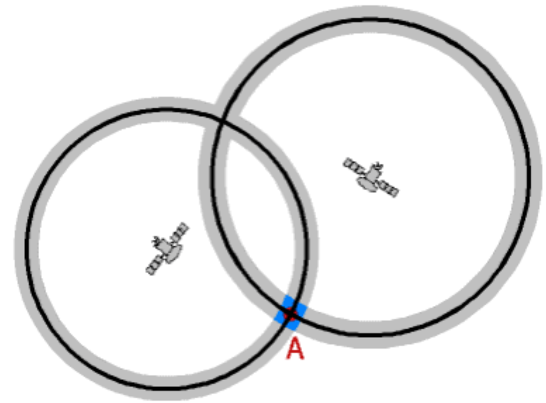
- Distance Error: estimate of average distance measurement error to a satellite

- We want both PDOP and Distance Error to be **SMALL**

# PDOP – Positional Dilution of Precision

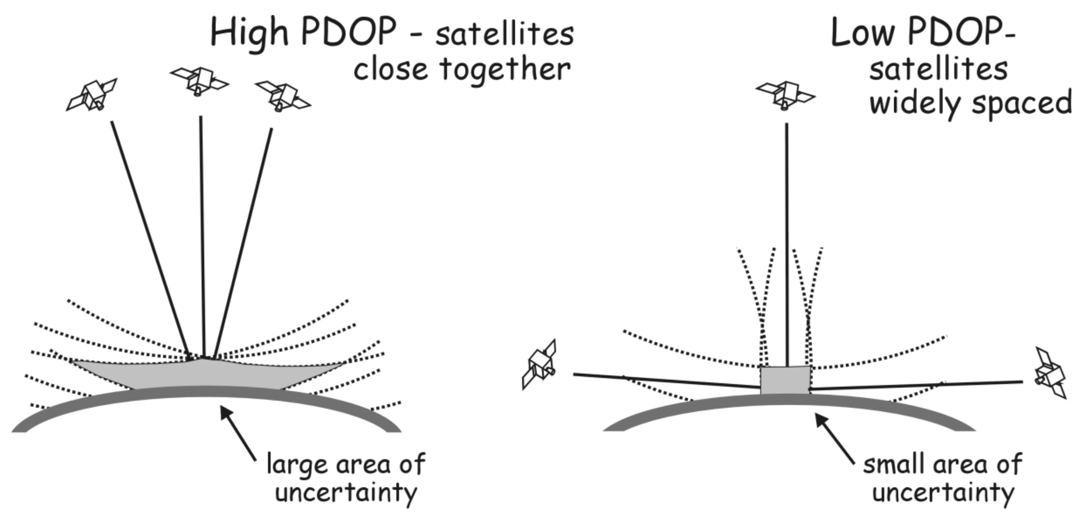



Bad Geometry




Good Geometry

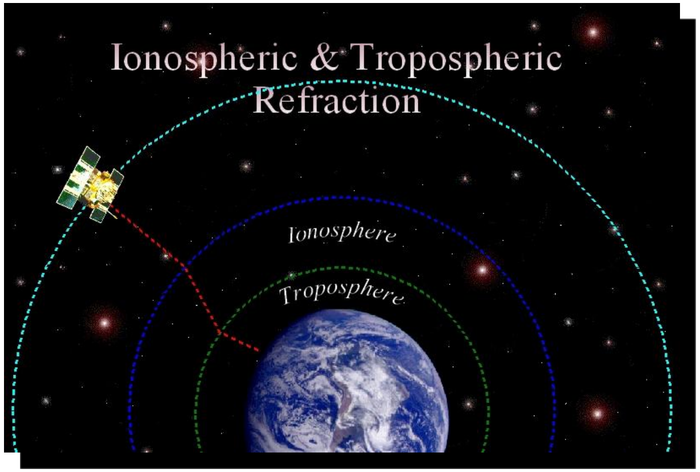
- Factors to achieve low PDOP
  - # of SVs in GPS Constellation
    - Max: 32
  - # of channels in GPS receiver
    - 12-channel all-in-view
  - Antenna gain at low elevation
    - Track at < 5° elevation

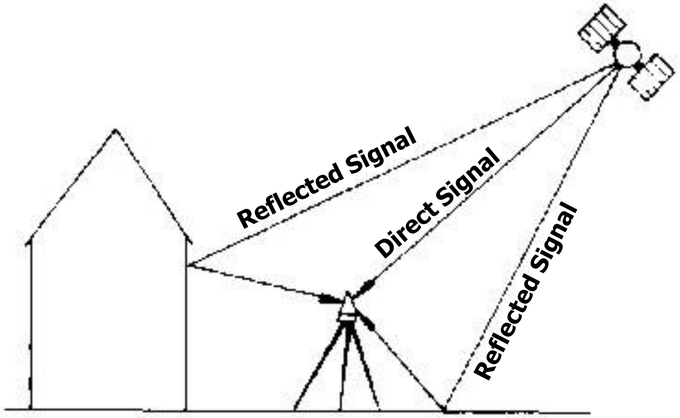



# Distance Measurement Error Sources

| Error Source | Civilian SPS C/A | Military PPS P(Y) |
|---|---|---|
| Satellite clocks | 1.1 m | 1.1 m |
| P(Y)-C/A group delay | 0.3 m | 0 m |
| Satellite position | 0.8 m | 0.8 m |
| Ionosphere | 7.0 m | 0.1 m |
| Troposphere | 0.2 m | 0.2 m |
| Receiver noise | 0.1 m | 0.1 m |
| Multipath | 0.2 m | 0.2 m |
| Selective Availability | -- | -- |
| **Total Distance Measurement Error** | **7.2 m** | **1.4 m** |

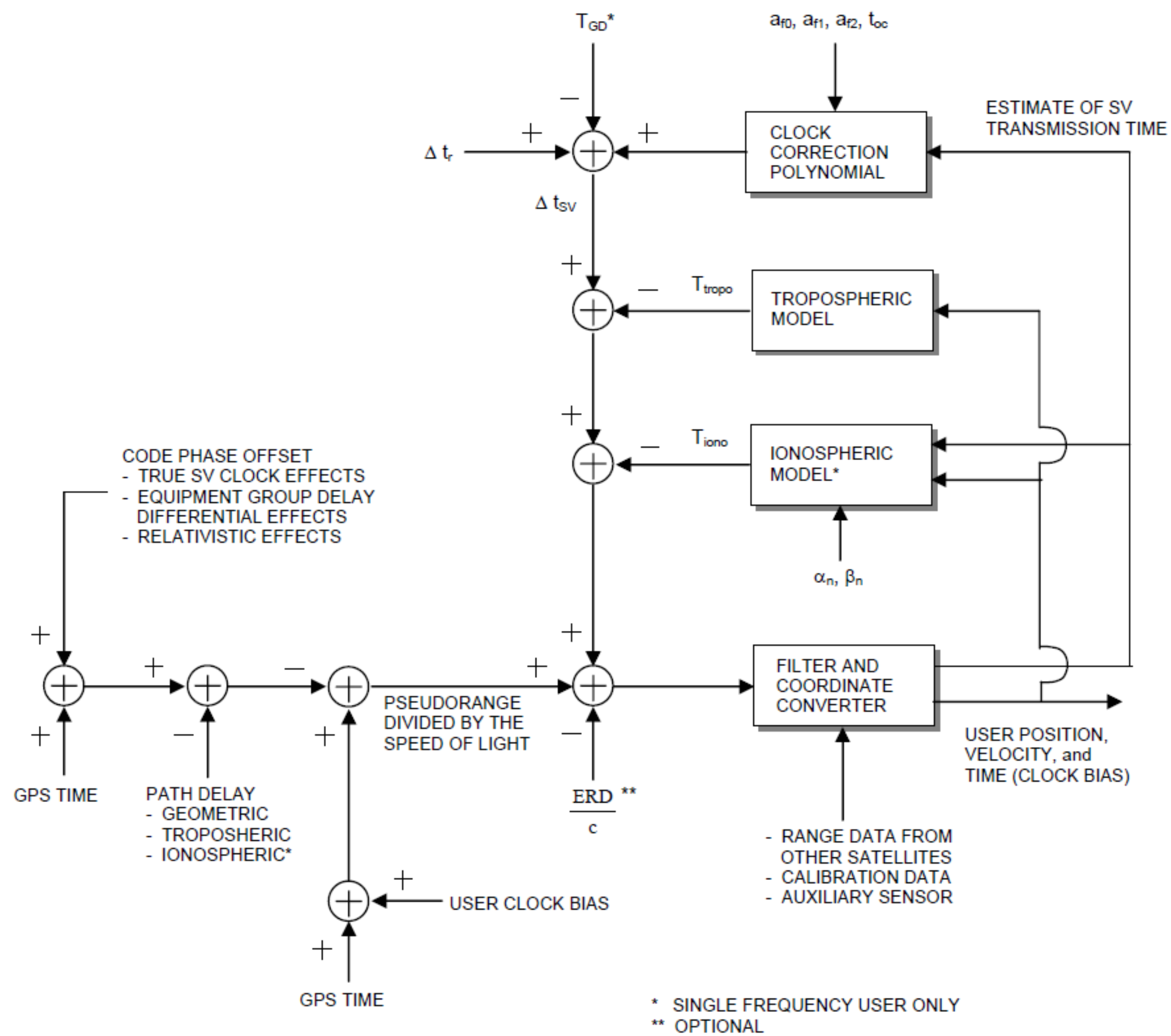
- All values are 1-sigma average for a quality GPS receiver
- Worst-case values can be much much larger




Multipath

# Error Correction Diagram




From IS-GPS-200D

# Integrity Enhancement: RAIM and FDE

- Fault Detection and Exclusion (FDE)
  - Suppose there is one faulty distance measurement with unacceptably large error
  - Need minimum **5** distance measurements to detect the fault
  - Need **6** distance measurements to exclude the faulty measurement

- A simple example with 2 variables to illustrate the idea

1st measurement: $x + y = 2$
2nd measurement: $x - y = 0$
3rd measurement: $2x + y = 6$
4th measurement: $x + 2y = 3$

Can you determine which measurement is faulty?

No, we can not.

- A number of algorithms are developed for fault exclusion
  - Some algorithms require user input of exclusion level (e.g., 200 meters)
  - Other algorithms can set exclusion level adaptively according to current conditions

# Integrity Enhancement: RAIM and FDE

- Receiver Autonomous Integrity Monitoring (RAIM) Algorithm
  - Input:
    - Standard deviation of distance error
    - Satellite geometry
    - Maximum allowable probability for a false alert (e.g. 10^-5 per hour)
    - Maximum allowable probability for a missed alert (e.g., 10^-3)
  - Output:
    - Horizontal Protection Level (HPL)
  - Alarm the pilot if HPL > Horizontal Alert Limit (HAL)
  - RTCA defines HAL as
    - 2 nmi for En Route
    - 1 nmi for Terminal
    - 0.3 nmi for Non-Precision Approach

- An example
  - The GPS receiver reports the estimate of horizontal position error = 3 meters
  - The GPS receiver calculates the HPL = 50 meters

# Concept of DGPS

- GPS user without external aiding can attain accurate position and time
  - Civilian SPS C/A: 10 meters and 30 ns for 95% of the time
  - Military PPS P(Y): 5 meters and 15 ns for 95% of the time

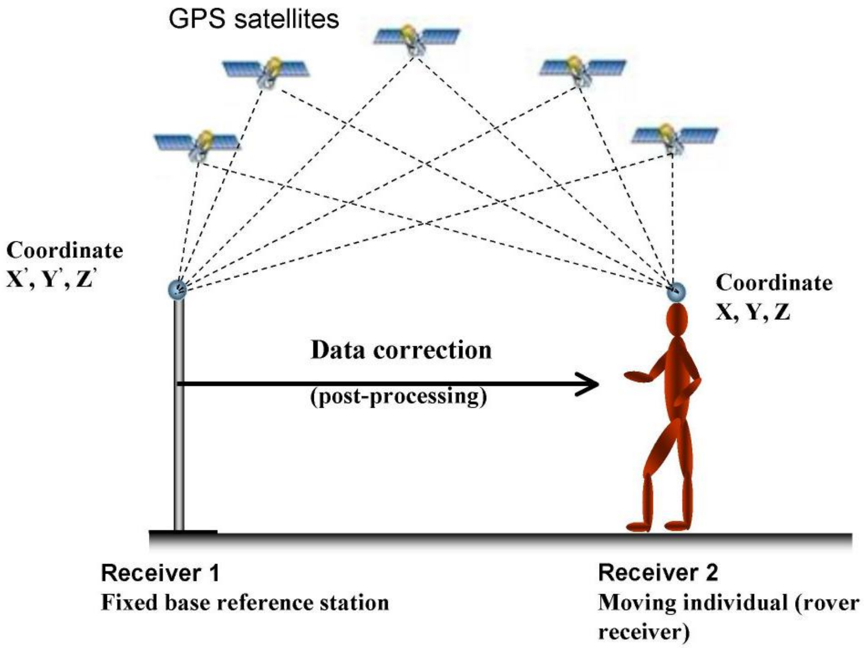
- Differential GPS (DGPS) technique allows user to achieve much better position accuracy, < 1 meter

- Many GPS error sources are highly correlated over space and time
  - In other words, receivers close to each other observe roughly the same amount of distance measurement error due to these error sources
  - Satellite clock error
  - Satellite position error
  - Tropospheric error
  - Ionospheric error

- Receiver noise and multipath errors are uncorrelated

# Local-Area DGPS

- Base Station (BS) is a GPS receiver located at a known location
- BS calculates the DGPS corrections for each satellite distance measurement
  - Correction = "True" Distance – Measured Distance
- BS broadcasts the DGPS corrections to DGPS users (Rovers)
- A DGPS user applies the corrections to its distance measurements and calculates an improved position solution
  - Improved Distance = Measured Distance + Correction

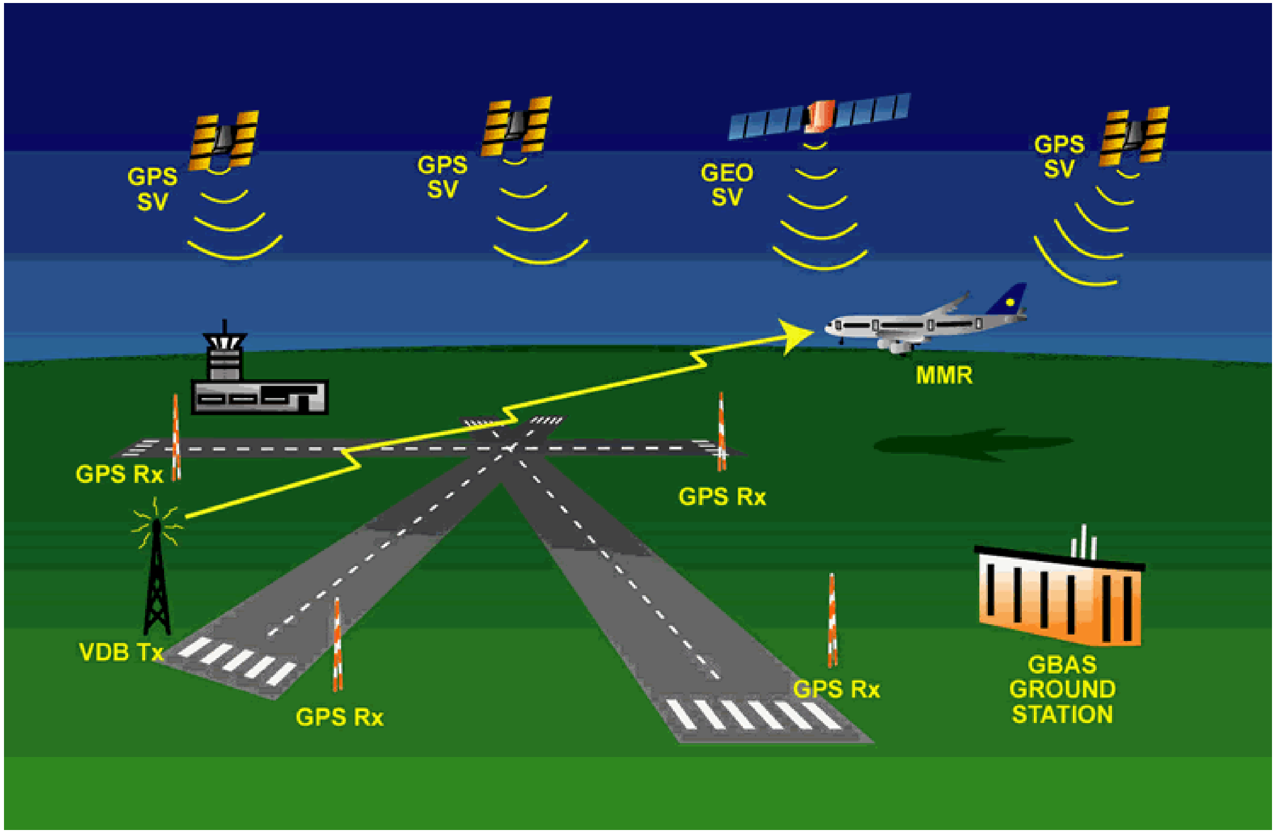



LOS error = 0.3 m + 1--6 cm/km x baseline (km)

Note: User cannot use a mix of DGPS corrected and uncorrected distance measurements to calculate a position solution. Why? …

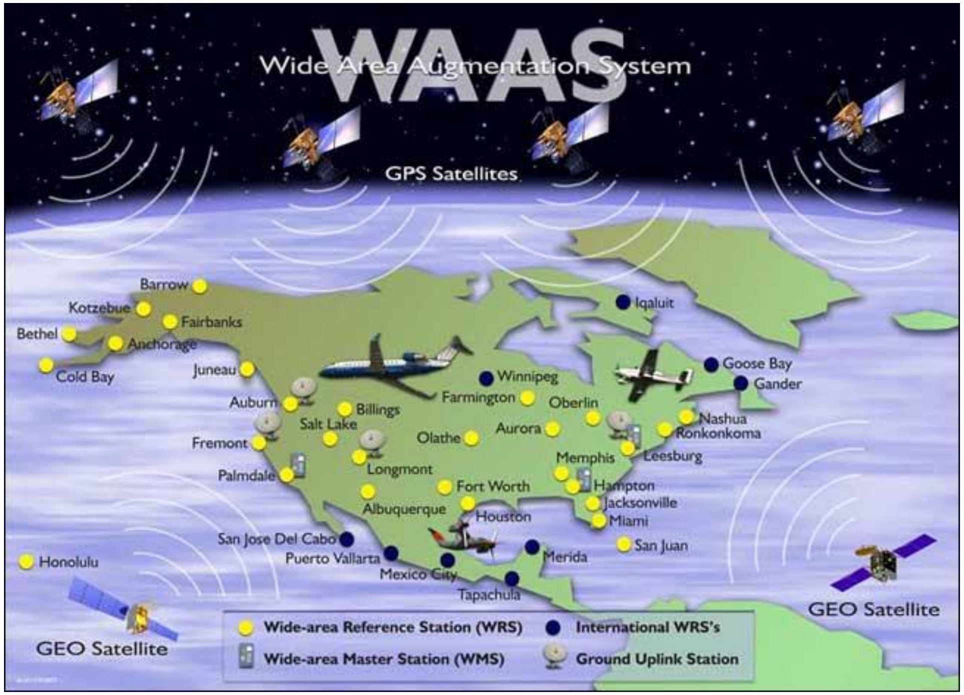
# Ground Based Augmentation Systems (GBAS)

- Correction and integrity information is broadcast to the user using terrestrial communication links
  - Examples: SCAT-1, LAAS, JPALS, etc



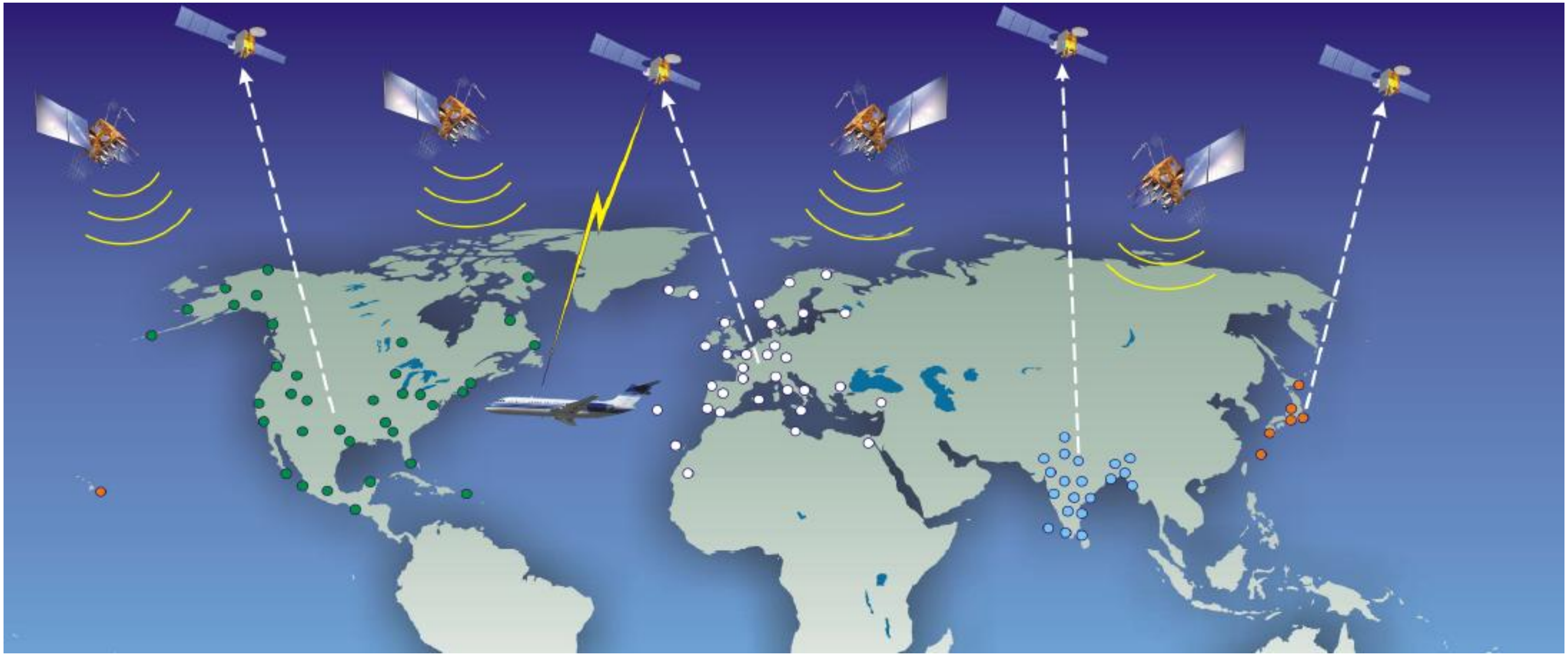
# Wide-Area DGPS

- WADGPS Goal is to attain meter-level accuracy over a large region
  - Reference stations are spread out across the region
  - Process raw data from each reference station
  - Break out the total distance error into components
    - SV ephemeris error, SV clock error, and ionospheric error
  - Estimate the variation of each error component over the entire service region
  - Accuracy does not depend on the proximity of the user to a single station



# Space Based Augmentation Systems (SBAS)

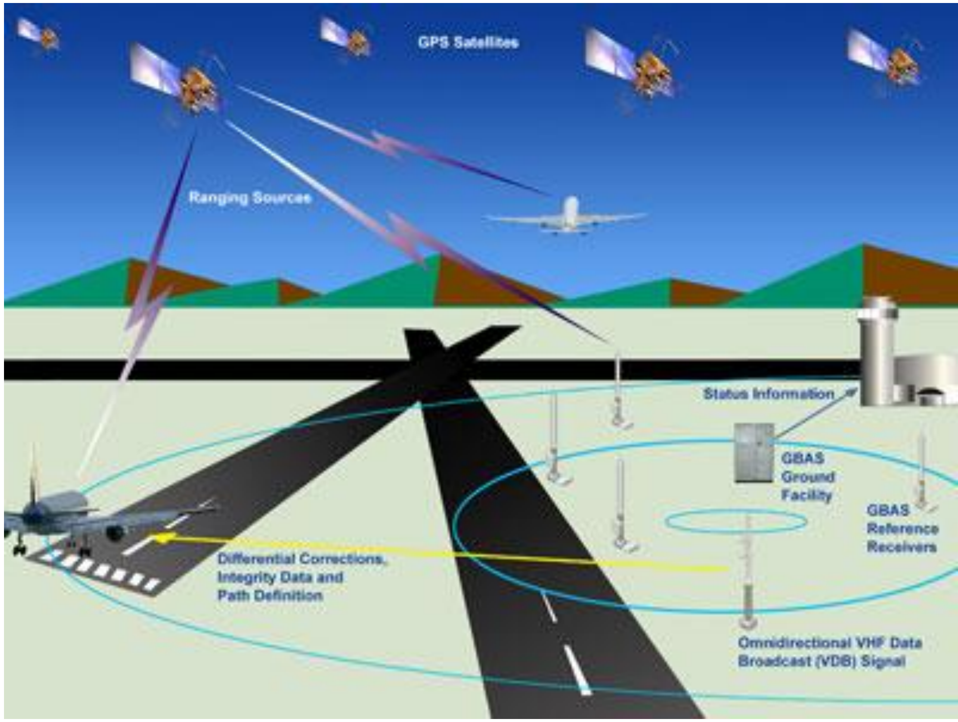
- Correction and integrity information is broadcast to the user using satellites
  - Examples:
    - Regional coverage: WAAS (US), EGNOS (Europe), GAGAN (Inida), MSAS (Japan),
    - Global coverage: OmniSTAR, StarFire



# Future Systems for Civilian Aviation

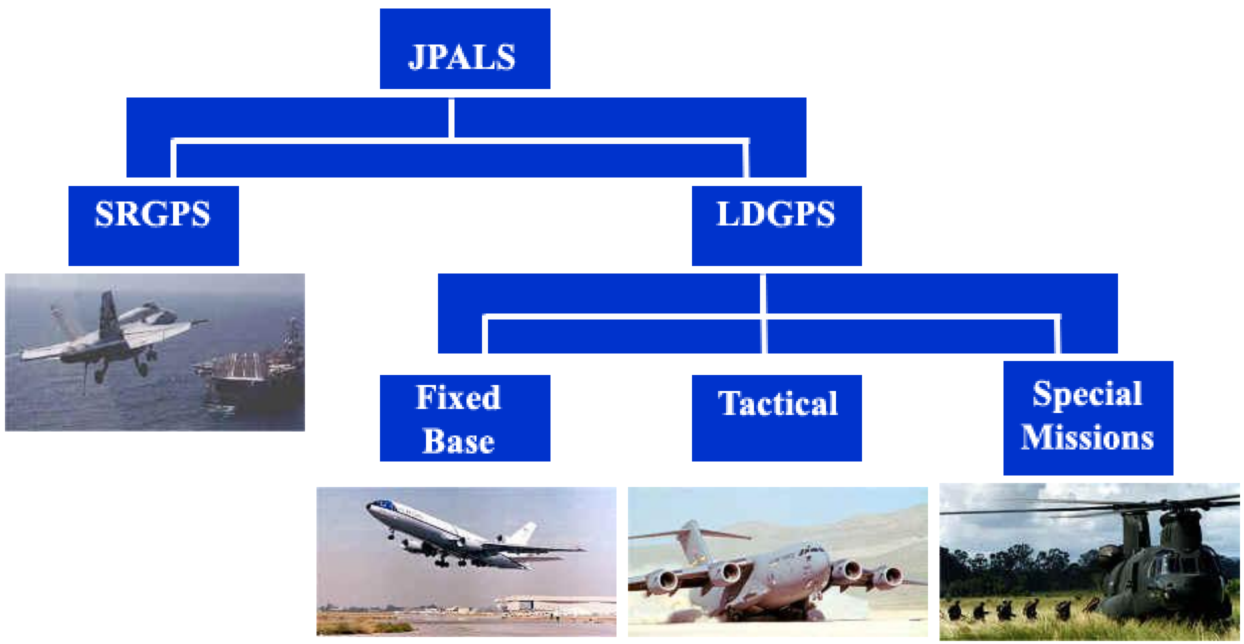
- GBAS – Ground Based Augmentation System
  - Defined by the International Civil Aviation Organization (ICAO)

- LAAS – Local Area Augmentation System
  - FAA version of GBAS
  - For Category I, II, III precision approaches
  - Eventually support automatic landings
  - Single facility with three or more reference receivers
  - Provide carrier-smoothed range correction
  - Extremely high accuracy, availability, and integrity
  - 0.5 meter (95%) accuracy within 45 km
  - Broadcast via a 31.5 kbps VHF link
  - Status: prototyping phase



# Future System for Military Aviation

- Joint Precision Approach and Landing System (JPALS)
  - Precision approach and landing system for DoD
  - Similar in concept to Civilian LAAS, based on DGPS or CP-DGPS technology
  - Modular avionics and ground/shipboard components to provide a range of autonomous landing and system configurations.
  - Allow operations through a range of threat environments
  - Will replace legacy systems (ACLS, PAR, ILS, and TACAN)
  - Status: currently in SDD phase, expect IOC by 2016 and FOC by 2026



# Conclusion

- Basic concepts of GPS and DGPS from a user perspective

- Topics not mentioned include:
  - GPS signal characteristics
  - Signal acquisition, tracking, and data demodulation
    - Code and carrier tracking loops
    - Phase lock loops and frequency lock loops
    - Formation of pseudorange, delta pseudorange, and integrated carrier Doppler phase
  - Carrier-phase DGPS / Real Time Kinematic (RTK)
  - Attitude determination
  - Integration of GPS with Inertial Navigation System, INS/GPS
  - Integrity, Availability, and Continuity

Thank you for your interest

- References for further reading
  - IS-GPS-200D, Navstar GPS Space Segment/Navigation User Interfaces
  - E. D. Kaplan and C. J. Hegarty, *Understanding GPS: Principles and Applications*
  - P. Misra and P. Enge, *Global Positioning System: Signals, Measurements, and Performance*