Chapter 1

Fundamentals of Satellite Positioning

What do Users Want?

- Location & navigation with the required
  - Availability
  - Accuracy
  - Reliability and integrity
  - Continuity (seamless outdoor-to-indoor and vehicles-to-pedestrians)
- What are the required performance levels?
  - Minimum Operational Performance Standards (MOPS) defined for certain applications (Example: E911 – 150 m 95%)
  - For most users - The higher, the better!
  - *Velocity needed in some cases (motion detection)*
- *Is“10 m in 10 s anywhere at any time” realistic?*

Performance Measures

- Accuracy: Ability of GPS to maintain the position within a total system error
- Availability: Percentage of time that GPS is usable
- Continuity: The level of interruption when the surrounding environment changes
- Reliability: Ability to detect faults and to estimate the effects that undetected faults may have on solution
  - Internal Reliability
    - Quantifies the smallest fault that can be detected on each observation through statistical testing of the least-squares residuals
  - External Reliability:
    - Quantifies the impact that an undetected fault can have on the estimated parameter

Origins of GPS (1/2)

- Predecessor was the US Navy's TRANSIT system which was deployed in the 1960s and operational until early 1990s– concept was to measure the integrated Doppler over time to form range differences

- The TIMATION project was initiated in 1964 whereby precise clocks would be flown in space to provide both time and position information

- In 1968, US DoD issued new requirements for precisely locating military forces worldwide – NAVSTAR GPS concept approved in 1973

- By June of 1974 Rockwell had been selected as the satellite contractor. To maintain focus of the program the JPO adopted the following motto:

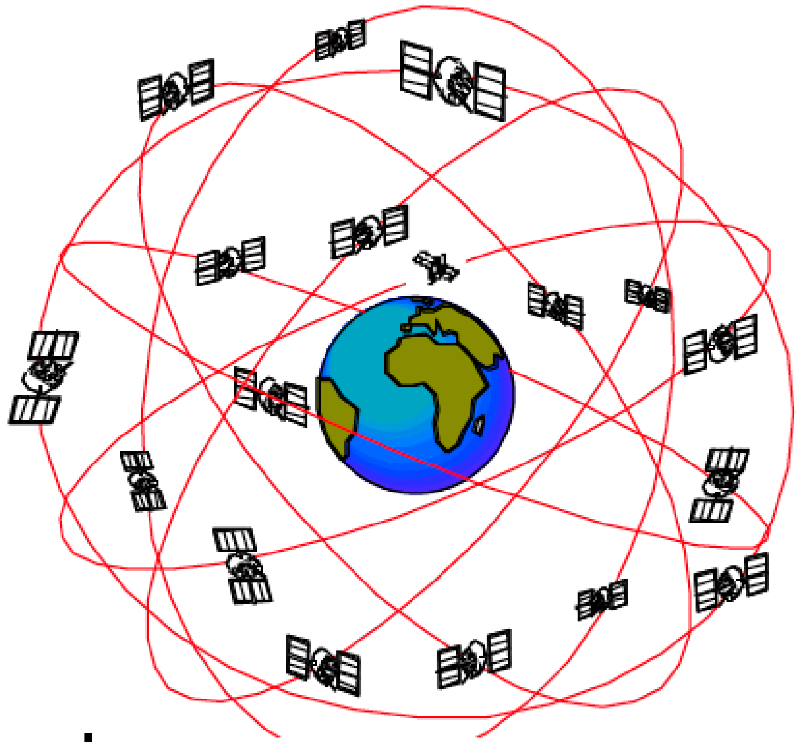
The mission of this program is to:
1. Drop 5 bombs in the same hole, and
2. Build a cheap set that navigates (<$10,000)
and don't you forget it!

Origins of GPS (2/2)

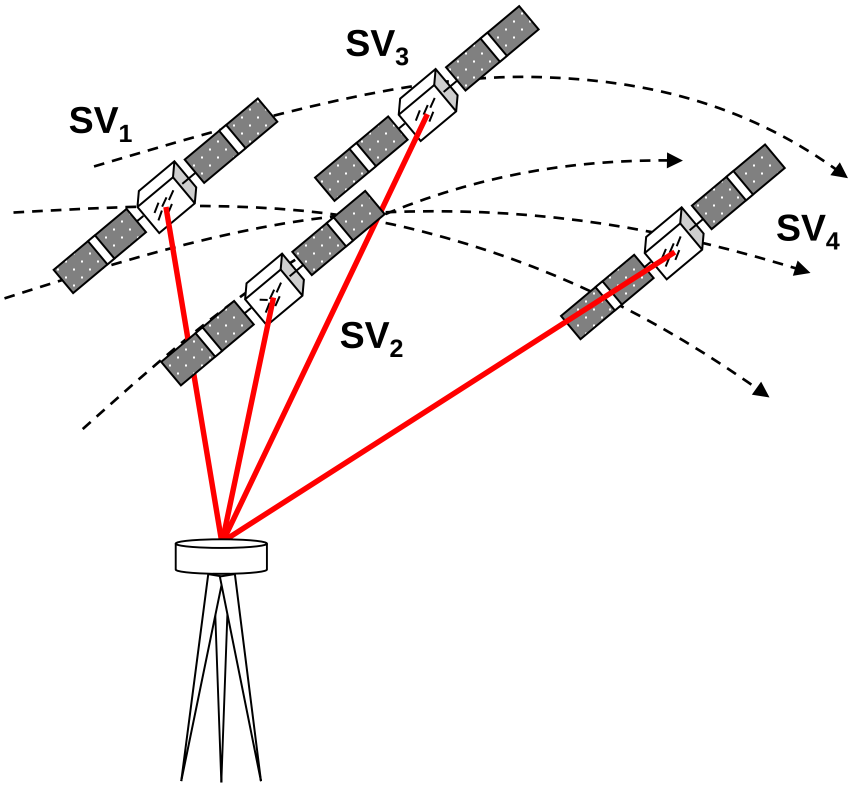
- A lot of work was put into the development of the signal structure (pseudorandom noise codes) and anti-jamming capability (spread spectrum) – 621B Program
- Initial testing of the system was done in New Mexico whereby pseudo-satellites were installed on the ground and aircraft with prototype GPS receivers tracked the signals
- First prototype satellite launched in 1978 – the control segment was deployed and working and five receivers were being tested
- First commercial GPS receiver was the Stanford Telecommunications (STel) 5010 which cost > US $150,000. The next generation GPS receiver was Texas Instruments TI 4100 (US $125,000)
- The total system cost is > $6 billion. Initial operational capability (IOC) in December 1993. Full operational capability in July 95

GPS Constellation

- **Nominal constellation:**
  - 24 satellites + active spares (currently > 30)
  - 6 orbital planes – 55 deg inclination
  - 12-hour (sidereal) periods
  - 20,000 km + altitude
- **Worldwide, continuous coverage**
- **Line-of-sight, all weather system**
- **Currently transmits on three carrier frequencies:**
  - L1 = 1575.42 MHz
  - L2 = 1227.60 MHz
  - L5 = 1176.45 MHz
- **Frequency and time synchronized signals**
- **CDMA modulation codes for ranging**
  - C/A, P(Y), L2C, and M-codes
  - (L5 1st launch – Apr09)



Trilateration in Space



Unknown:

- Latitude (Φ)
- Longitude (λ)
- Height (h)
- Receiver clock bias (dT)

Known:

- Satellite orbital parameters
- Precise time

Observations:

- Receivers measure a *biased* propagation distance of signals from several satellites (i.e. *pseudorange*)
- At least four observations are required to solve for all 4 unknowns (Φ,λ,h,dT)

Two primary differences from terrestrial trilateration:

- Targets (satellites) moving (~4 km/s)
- As a result, the geometry is changing as a function of time

Pseudorange Measurement (1/2)

- **Range and propagation time are directly related by speed of light in a vacuum (c = 299,792,458 m/s)**
  - GPS is fundamentally a timing system!
  - At speed of light, **1 ns ~ 30 cm** propagation distance
  - Range of 67-87 ms propagation time from satellite (SV) to ground

- **Accurate propagation time relies on several factors:**
  - A standard reference time scale (offset and rate)
  - Accurate and precise clocks at transmitters
  - Accurate and precise clocks at the receiver
  - A knowledge of the medium the signal is traveling through

Pseudorange Measurement (2/2)

- **Assuming accurate clocks at both transmitter and receiver, time transfer accomplished as follows:**

- **Transmitted signal encodes time of transmission:**
  - Binary pseudo-random code (PRN) is synchronized with SV's clock, and
  - Navigation data carries encoded time of week (TOW)

- **Receiver measures propagation time:**
  - Decoded TOW and NAV bit boundaries give approximate time (~ 1 ms)
  - Correlation of received and local PRN codes gives precise time (< 0.1 μs)
  - $TOW_{Rx} – TOW_{Tx} = T_{Prop}$
  - Except, receiver clock not synchronized with SV clocks...
  - ...thus, 4th observation required for 3 coordinates + 1 clock offset

- **How are we sure that transmitter and receiver clocks are measuring the same thing?**

Navigation Solution (1/2)

Simple application of cartesian geometry:

- Four equations with 4 unknowns

$$R_1 = \{[x_{s1} - x_g]^2 + [y_{s1} - y_g]^2 + [z_{s1} - z_g]^2\}^{1/2} + cdT$$
$$R_2 = \{[x_{s2} - x_g]^2 + [y_{s2} - y_g]^2 + [z_{s2} - z_g]^2\}^{1/2} + cdT$$
$$R_3 = \{[x_{s3} - x_g]^2 + [y_{s3} - y_g]^2 + [z_{s3} - z_g]^2\}^{1/2} + cdT$$
$$R_4 = \{[x_{s4} - x_g]^2 + [y_{s4} - y_g]^2 + [z_{s4} - z_g]^2\}^{1/2} + cdT$$

- R_i's are the ranges (within a bias – cdT) measured by the receiver)
- x_{si}, y_{si} ,and z_{si} (satellite coordinates) are computed from known SV orbital parameters and approximate time
- x_g, y_g,z_g and cdT are the unknowns to be determined
- Equations must be linearized using Taylor's series

Navigation Solution (2/2)

- What if more than 4 pseudoranges are measured?
  - How do we solve an over-determined system?
  - What are the advantages of having more than 4 satellites?

- How are non-linear equations solved?
  - Non-linear system of equations
  - More than 1 solution may be possible – how do we find the correct solution?

Section 1.3	Space, Control and User Segments

GPS Space Segment (1/2)

- **Hardware:**
  - Radio Transceivers
  - Atomic Clocks
  - Computers
  - Solar Panels (7 m^2)
  - Propulsion System

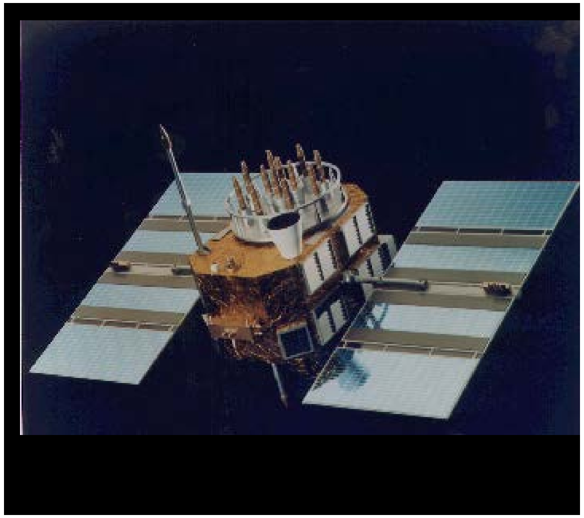
- **Block I (Launched between 1978 – 1985):**
  - Space Vehicle (SV) numbers 1 – 11
  - Intended for R&D (4.5 year expected lifespan)
  - No Anti-Spoofing capability

- **Block II (Launched between Feb 1979 – Oct 1990):**
  - Space Vehicle (SV) numbers 12 – 21
  - Still require three uploads per day (expected lifespan of 7.5 years)

GPS Space Segment (2/2)

- **Block IIA (1990 - 1997):**
  - Space Vehicle (SV) numbers 22 – 40
  - Only require one upload per day
- **Block IIR (1997 - present):**
  - Replenishment satellites
  - Improved communications and autonomous operation capabilities
  - Longer design life (10 years)
- **Block IIR-M (first launch – Sep 05):**
  - Modified Block IIR
  - Adds Military M-code and civil code on L2 (L2C)
  - A further modified IIR-M with L5 was launched in Apr09
- **Block IIF:**
  - Adds L5 signal (1176.45 MHz)
- **Block III:**
  - Enhanced capabilities (under development)
  - Launch 2 satellites at a time

GPS Satellites Types In Use



Block II/IIA

- •2 Cesium clocks
- •2 Rubidium clocks

Block IIF (2008+)

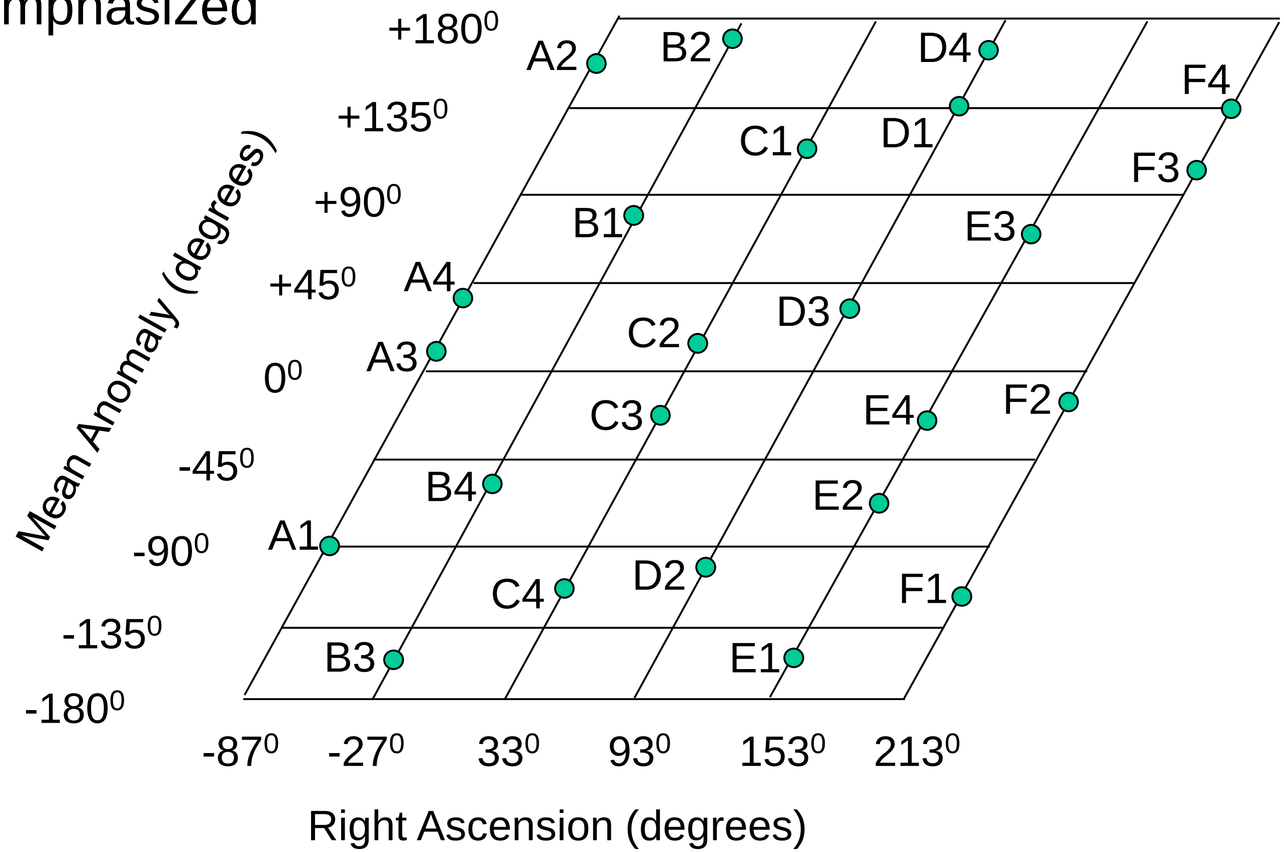
- •6 short term SVs
- •45 long term SVs
- •In orbit till 2020
- •15 year life span
- •4710 Ib weight
- •Autonomous
  operation for 60 days

Block IIR / IIR-M

- •3 Rubidium clocks

GPS Constellation

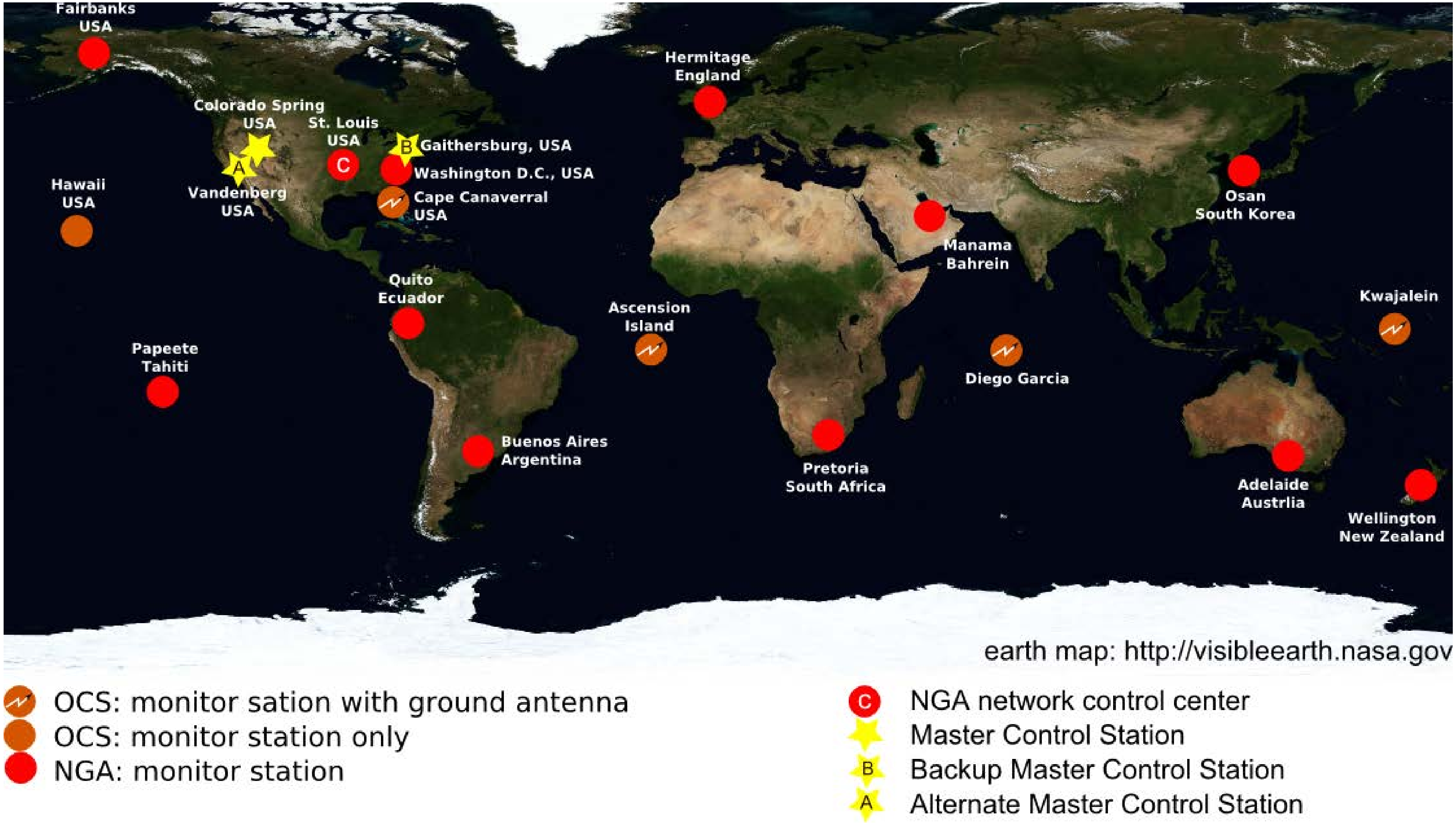
- Six orbital planes, 60 degrees apart, 55 degree inclination
- Four or five satellites per plane
- Satellite phasing (location) optimized for coverage with some world areas emphasized



Current GPS Constellation (16Jun2013)

ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt

GPS Operational Control Segment (OCS)



OCS Modernization (1/2)

GPS Legacy Accuracy Improvement Initiative (LAII)

- Undertaken by National Geospatial-Intelligence Agency (NGA) and GPS JPO
- Objectives
  - 100% SV monitoring capability from ground stations
  - 50% Improvement in Kalman Filter orbits
  - 10% Improvement in SIS UREs
- Original 6 OCS monitoring stations augmented by NGA stations
- Updated geophysical, tropospheric, and solar radiation pressure models implemented
- Results...

OCS Modernization (2/2)

- Ground Control Monitoring availability increase to 100% from ~ 96%
  - Reduces chance of undetected error
  - Provides additional data for orbit prediction
- Improved orbital predictions ~44%
  - Due to above monitoring and adjusted Kalman Filter
- User Range Error (URE) improvement
- Additional monitoring stations provide more accurate frame of reference for earth monitoring

GPS User Segment

Military GPS Users:

Civilian GPS Users:

- Navigation was primary focus of GPS developers, but surveying community quickly adopted the system for high accuracy positioning
- The use of GPS in the civilian community is expanding rapidly due to the decrease in receiver costs (i.e. 10’s of thousands of $ to less than $1)
- Location-based services is the largest segment with 100’s of millions of units
- Civil community much larger than military community which has implications in receiver technology (rather than vice versa)
- Mobile consumer devices has revolutionized the typical GPS user

Provision of Service

- **Access is free for all users:**
  - There has been discussion of charging users in the future but this is not really practical
  - Most likely option would be to have other countries partially support the system
- **US Government will give a 10 year notice of cancellation:**
  - Level of accuracy has been guaranteed
- **Day to day management is done by DoD:**
  - Input from the civil community through Department of Transportation (DoT)
  - National Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee - Replaced Interagency GPS Executive Board (IGEB) in August 2005
  - There has been concern expressed from the international community that there should be more international input
- **2nd civilian frequency adopted in 1998: 1227.60 MHz (L2)**
- **3rd civilian frequency adopted in 1999: 1176.45 MHz (L5)**
- **New signal structures now available on L2C, L5 and L1C**

GPS Levels of Service

- **SPS – Standard Positioning Service**
  - Civilian service available for all users
  - Historically, access to only a single ranging code on L1 (C/A)
  - Less accurate, lower bandwidth signals

- **PPS – Precise Positioning Service**
  - Higher-accuracy service for authorized users
  - High-bandwidth P(Y) ranging code on 2 frequencies (L1 / L2)
  - Unauthorized access denied by *Anti-Spoofing* (AS)

- **Future service levels will be enhanced for all users by addition of new codes / frequencies (e.g. L2C, L1C, L5)**

S.A. and A.S.

Selective Availability (S.A.): *- Set to zero on May 1, 2000 and removed in Sep 2007*

- Controlled accuracy of GPS available to non-authorized users
- Effected through satellite clock dithering (δ) and broadcast orbit accuracy (ε) degradation
- Various S.A. levels could be implemented
- Important only if one has to deal with pre-May2000 data

Anti-Spoofing (A.S.):

- Prevents receivers from being spoofed by fake signals
- Effected through encryption of (long) P code (time shifting is sufficient). Encrypted P code becomes Y code
- P code on L1 and L2 no longer possible with standard code correlation techniques

Sources of Position Error

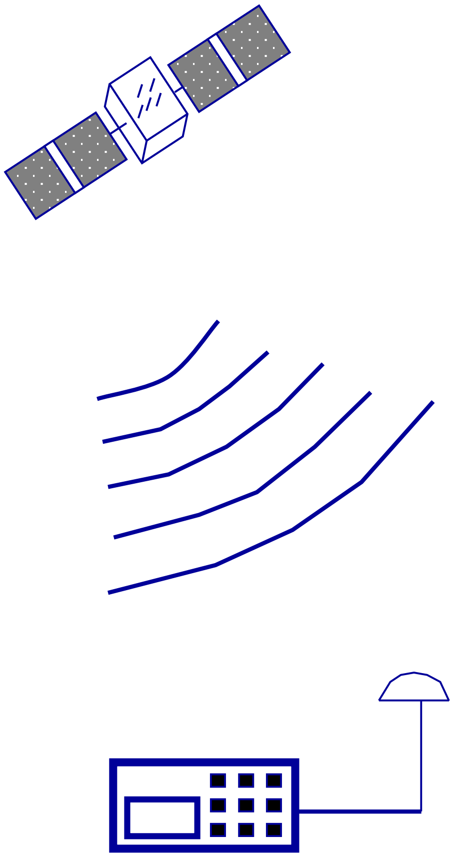
Two main factors affecting PNT accuracy:

1. Ranging errors
2. Geometry of solution

Key Questions:

- How do we characterize satellite geometry?
- What if we know the height (i.e. marine navigation)?
- Are there position discontinuities when satellites drop out or are added?
- How is position performance affected when using least-squares versus filtering? What are the advantages and disadvantages?
- What are the advantages of having even more satellites in space (i.e. GPS + GLONASS)?

Major Pseudorange Error Sources

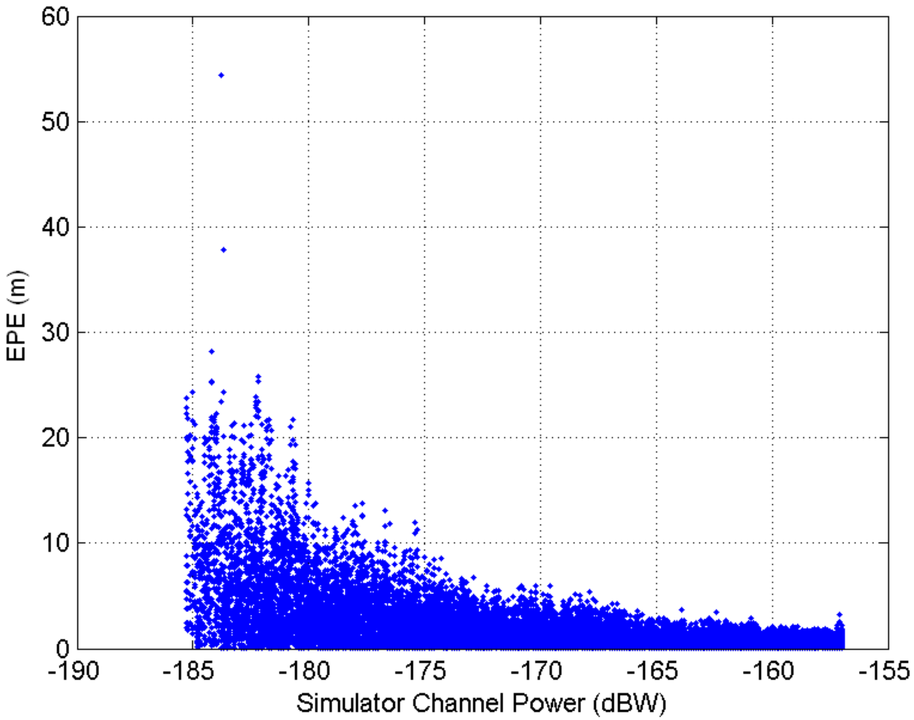


- Satellite Errors (1σ):
  - Orbit & Clock: 1 - 2 m
- Propagation Errors:
  - Ionosphere: 1-30 m
  - Troposphere: 0.2 m
- Receiver Errors
  - Code Multipath: 0.01-10 m
    - NLOS: Unlimited
  - Code Noise: 10-100 cm
    - NLOS: up to 25-30 m
  - Carrier Multi.: 1–50 mm
  - Carrier Noise:0.2–2 mm

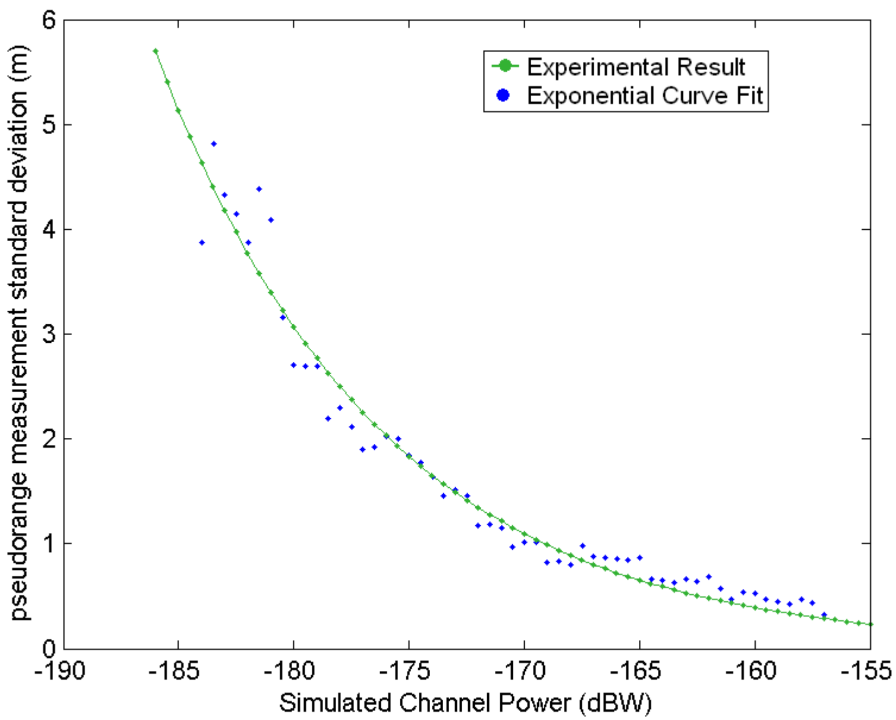
Measurement Noise Vs Signal Attenuation

- As the received signal power decreases, the measurement uncertainty increases

Pseudorange Error vs Power



Pseudorange Standard Deviation vs Power



User Equivalent Range Error - UERE

- UERE is the square root of the quadratic sum of errors (thus 1 sigma) affecting the accuracy of measured ranges and is a function of
  - Satellite errors, propagation errors, receiver related errors
- Depends on
  - Receiver type, L1 vs L1/L2 (for the ionosphere), noise and prevailing multipath, tropospheric model, satellite orbit and clock errors
- Largest source of uncertainty with L1 measurements is the ionosphere

$$UERE(1\sigma) = \sqrt{d\rho^2 + dt^2 + d_{ion}^2 + d_{trop}^2 + \varepsilon_P^2 + \varepsilon_{multi.}^2}$$

- Observed UERE is typically 1-3 m for L1 receivers under an average ionosphere. Will drop near 1 m when L2C signals are available on all SVs

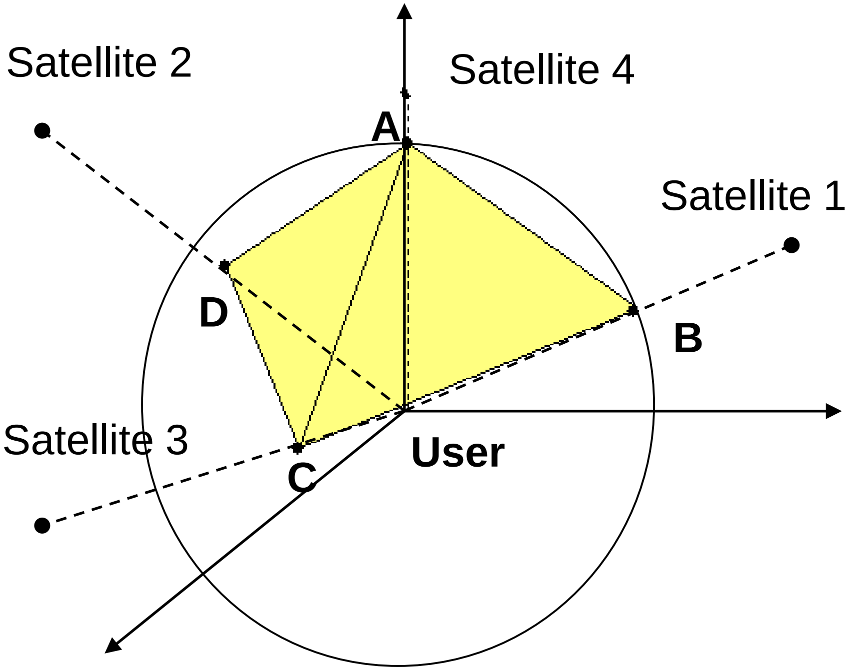
Dilution of Precision (DOP) – Measure of Geometry

- Geometry is measured through the Dilution of Precision (DOP)
- DOP is related to the volume formed by the intersection points of the user-satellite vectors, with the unit sphere centered on user

Note[1]: *Larger volumes give smaller DOP*

Note[2]: *Lower DOP values give better position accuracy:*

Position Accuracy = DOP x Range Accuracy



- For a four-satellite configuration, the best geometry is when there is one satellite at the zenith and the other three at elevation 0 and equally spaced in azimuth (i.e. every 120°)

Using UERE and DOP to Get Position Accuracy

- Positioning accuracy = DOP x UERE
  - Horizontal accuracy (DRMS) = HDOP (Horizontal DOP) x UERE
  - Vertical accuracy (1σ) = VDOP (Vertical DOP) x UERE
- If either DOP or UERE is poor (high numerical values), the positioning accuracy is poor
- DOP can change quickly due to satellite motion and satellite dropping in and out
- Indoor applications: both DOP and UERE can be poor!
- Example: a good HDOP is 2 or lower.
  - A good UERE outdoor is 10 m, giving a horizontal accuracy of 20 m
  - UERE is lower when the ionosphere is quiet
  - Indoor, the UERE can increase to 10's of m (due to higher noise and multipath) and the DOP to 10 – 100!

SPS Time-Transfer Accuracy

- **Accuracy is a function of real-time versus post-mission and of mode (single point versus differential):**
  - 30 cm is 1 ns (10^{-9} s). Since time and position accuracy (especially height) are correlated, it is possible to deduce timing accuracy in both single point and differential mode.
  - In order to actually transfer GPS time to an external device with a high level of accuracy, receivers must have the proper mechanization firmware.
  - In post-mission, time transfer may be more accurate if averaging or filtering can be made.
  - See (http://tycho.usno.navy.mil/gpstt.html) for relationship between GPS time and other time scales
  - Current UTC from U.S. Naval Observatory: (http://tycho.usno.navy.mil/utclock.html)

Signal Attenuation

GPS Best-Case Scenario

- Nominal received SNR (L1 C/A): -19 dB
  - Signal power: -160 dBW
  - Presumed noise density: -204 dBW/Hz in 2 MHz bandwidth
- Typical detection threshold: +14 dB
- Nominal processing gain required: 33 dB

GPS Under Foliage / Urban Canyons

- 0-20 dB additional attenuation / fading (typical)
- Up to 53 dB processing gain desirable

GPS Indoor

- 0-40+ dB of additional attenuation / fading
- 70+ dB processing gain desirable

How to Acquire and Tracking Attenuated Signals?

- Normal integration time of LOS signals is 1-5 ms
- Increase integration time of IF in-phase and quadra-phase measurements to improve SNR
  - e.g. High Sensitivity GPS (HSGPS)
- Assisted GPS (AGPS) is used for real-time acquisition
  - SV nav message, Doppler shift transmitted from nearby LOS stationary receiver, time
- Integration time limited by many factors
  - e.g. rx oscillator noise, user motion
  - Currently up to a few 100’s ms

HSGPS Limitations

- Although HSGPS theory would seem to provide a means to navigate under adverse operational conditions, several practical problems must also be considered
- Some of the more significant problems due to low signal power include
  - Increased measurement noise
  - Poorer statistical reliability
  - Degraded satellite geometry effects (DOP)
  - Increased multipath and echo-only signals
  - Signal cross-correlation
  - Near-far problem

NLOS Positioning Accuracy

- If DOP = 10 and UERE = 50 m
  – Position accuracy = 500 m
- How to improve DOP?
  – Signal attenuation environment cannot be controlled
  – More satellites will help (GPS + GLONASS)
  – Add constraints (e.g. height using pressure sensors)
- How to improve UERE?
  – DGPS (to reduce correlated errors)
  – Detect and reject outliers (large reflected measurements), but this increases the DOP
  – Aiding with external sensors (relative improvement)
  – Outlier detection

Differential Correction Concept

- Several ranging error sources are correlated when measured or received near the same location on earth
  - Correlation distances up to 100s of kilometres
- Reference receivers with known position estimates can effectively estimate or observe ranging errors and apply them to other receivers
- Auxiliary systems (or “augmentation” systems) provide corrections to remote receivers to improve positioning

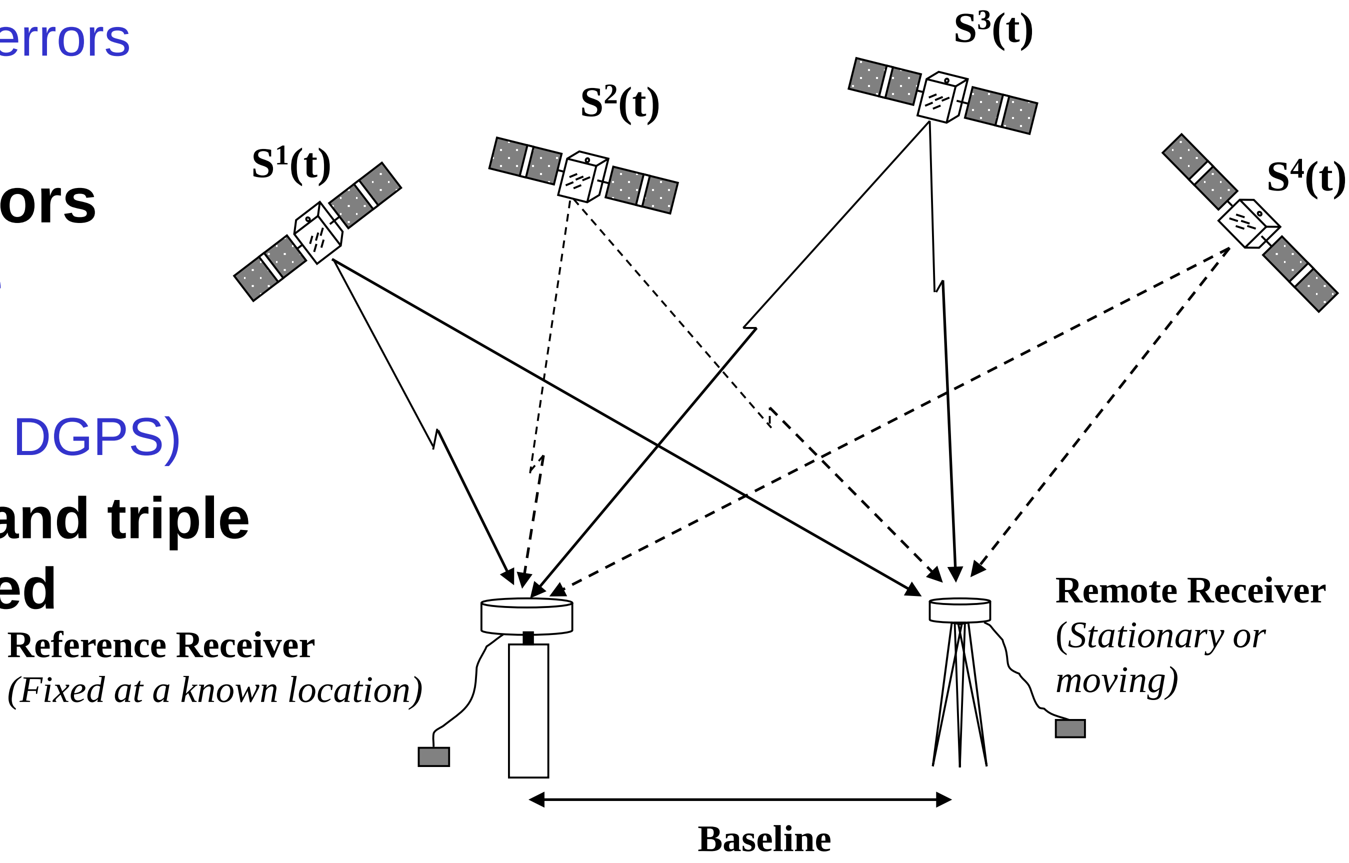
- Some terminology:
  - Satellite-based augmentation systems (SBAS)
  - Ground-based augmentation systems (GBAS)
  - Wide-area augmentation system (WAAS)
  - Local-area augmentation system (LAAS)

- Accuracy improvements to sub-metre, or sub-centimetre level possible!

Differential GPS Concept

- **Reduction or elimination of:**
  - Orbital errors
  - Atmospheric errors
  - Satellite clock errors

- **Remaining errors**
  - Receiver noise
  - Multipath
  - Ionosphere (L_1 DGPS)
- **Single, double and triple differencing used**



The Future: Multi-System GNSS

- New / modernized GNSS / SBAS systems coming online will enhance availability, accuracy, reliability, and choice:

- GNSS's
  - EU's Galileo Giove test satellites in orbit
  - Russia's GLONASS (near full coverage)
  - GPS Modernization underway
  - Chinese Beidou/Compass system emerging
- SBAS's
  - U.S. FAA's WAAS deployed
  - EU's EGNOS deployed
  - Japan's QZSS regional augmentation

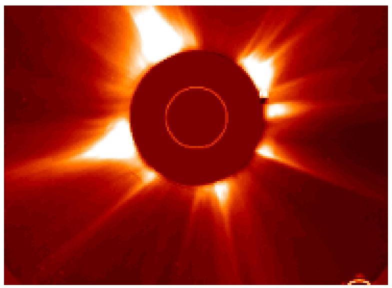
Section 1.6	GPS Modernization

GPS I/II Limitations

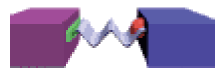
- Only one civilian authorized frequency (L_1) to 2005
- Prone to ionospheric effects & multipath
- Weak signals (-160 dBW limited use under masking)
- Limited number of satellites, although…
  - Accuracy is better than specs due to error correlation
  - Constellation has been over-populated for several years
- Also highly limited by…

See Chapter References: [4],[5]

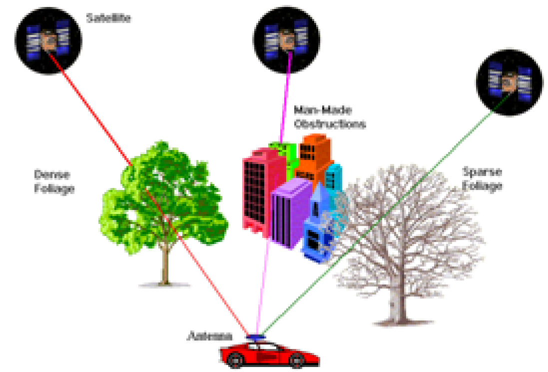
….Interference Sources



Ionospheric Scintillation

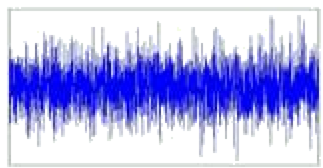


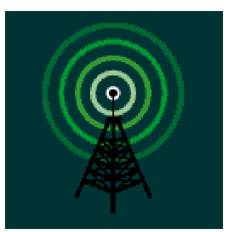
Doppler Shift



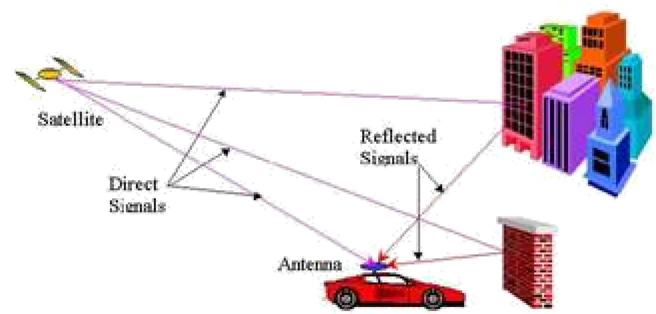
Signal Masking

Noise





Jammers (intentional or not)



Multipath

Section 1.6	GPS Modernization

Modernizing GPS

- **GPS is currently being modernized to meet the current and future demands of the civil community:**
  - Improved signals to support safety-of-life applications (e.g. aircraft landing)
  - Will consist of additional ‘coded’ signals to improve availability, integrity (timely notice of an unhealthy signal, continuity of service, and resistance to interference
  - Operational Control Segment (OCS) improvements underway

- **New signals will be phased in on future satellite launches**

GPS Modernization Schedule

- L2C (2nd civil signal): Began with IIR-M SVs in 2005
  - Provides 24 dB better protection than C/A against code cross correlation and continuous wave (CW) interference
  - Signal defined in ICD-GPS-200C
  - Current PRNs broadcasting L2C are 01,05,07,12,15,17,24,25,29,31 (ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt)
- L5 (3rd civil signal - 1176.45 MHz) began with IIF SVs in 2009
  - Improves signal structure for enhanced performance: Higher power (-154.9 dBW), wider bandwidth (24 MHz)
  - Signal defined in IS-GPS-705
  - Current PRNs broadcasting L5 are 01,24,25,27 (ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt)
- L1C (GPS III): Higher performance, first launch in 2015

All GPS Signals

Signal	Centre Frequency (MHz)	Modulation Type	Band-width (MHz)	Chip Rate (MHz)	Spreading Codes	Code Length	Signal Comp onent	Service Name
L1 C/A	1,575.42	BPSK(1)	2.046	1.023	Gold Codes	1023	N/A	Civil
L1 P(Y)	1,575.42	BPSK(10)	20.46	10.23	M-Sequences	Encrypted	N/A	Military
L2 P(Y)	1,227.60	BPSK(10)	20.46	10.23	M-Sequences	Encrypted	N/A	Military
L2CM	1,227.60	BPSK(1)	2.046	0.5115	M-Sequences	10,230	Data	Civil
L2CL	1,227.60	BPSK(1)	2.046	0.5115	M-Sequences	767,250	Pilot	Civil
L5-I	1,176.45	BPSK(10)	20.46	10.23	M-Sequences	10,230	Data	Civil
L5-Q	1,176.45	BPSK(10)	20.46	10.23	M-Sequences	10,230	Pilot	Civil
L1-M	1,575.42	BOC(10,5)	30.69	10.23	N/A	N/A	N/A	Military
L2-M	1,227.60	BOC(10,5)	30.69	10.23	N/A	N/A	N/A	Military
L1C	1,575.42	TMBOC(6, 1,1/11)	4.092	1.023	Weil Codes	10230	N/A	Civil

P. Ward et al (2005) In Understanding GPS: Principles and Applications, Eds. D.K. Kaplan and C.J. Hegarty, Artech House, pp. 153-241
Cao, W. (2009) Multi-frequency GPS and Galileo kinematic positioning with partial ambiguity fixing. MSc Thesis, Report 20285, Dept of Geomatics Eng, Univ. of Calgary.

Impact of GPS Modernization

- New signals and frequencies will provide:
  - Compensation for ionospheric delays
  - Better UERE (around 1 m)
  - Better and faster carrier phase ambiguity resolution
  - L2C dataless component for weak signal tracking
  - Higher L5 chipping rate will improve multipath rejection
  - For IIR-M/IIF SV: L1at -158.5 dBW, L2 at -160 dBW)
- ***Impact on (a) ambiguity resolution and IF solutions, (b) interference, (c) indoor location?***

Future SPS Positioning Accuracy With GPS Modernization

- Further expected improvements with modernization
- Further accuracy improvement to 6 m is expected with Operational Control Segment facility upgrades
- Note: These are **SPECIFIED** accuracies. Actual accuracies are often better!

SPS Horizontal Position Accuracy 95%		
S.A. Enabled	S.A. Disabled (set to zero)	SPS with two or more coded civil signals (C/A code on L2 and/or L5)
75 m	22.5 m	**8.5 m**

See Chapter References: [1],[3]

European Union's GALILEO

- **The European contribution to GNSS infrastructure:**
  - First phase provides a SBAS: EGNOS, that was available 1 October 2009.
  - Second phase provides a self-contained GNSS: GALILEO

- **Desire to counterweight GPS:**
  - Economic, technological and political issue due to the growing market for GNSS
  - Civil system with security protections based on services

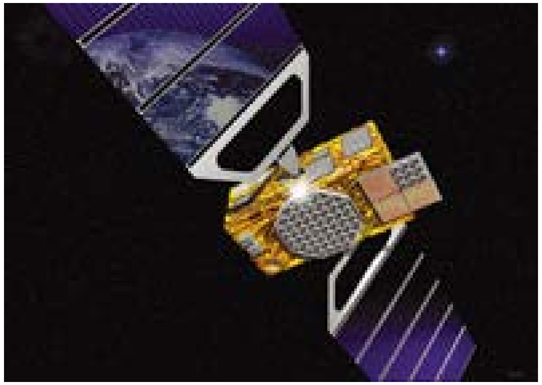
- **Desire to be interoperable with GPS:**
  - Offer to the user a better coverage, redundancy, reliability, etc.. when both systems will be used together
  - Most of the frequencies used will share GPS bands:
    - Ease GPS/GALILEO receiver design
    - Still some problems of inter-system interference to solve

GALILEO: A Service-Based GNSS

- **Five levels of services:**
  - Open Service (OS)
    - Free, comparable to GPS performance
  - Safety of Life Service (SoL)
    - Integrity message
    - Guarantee of service
  - Commercial Service (CS)
    - Additional signals with higher data rate and improved accuracy,
    - Guarantee of service
    - Limited broadcasting capacity from service centres to users
  - Public Regulated Service (PRS)
    - High continuity with controlled access
    - Two PRS navigation signals with encrypted ranging (reserved to public authorities, national security and law enforcement)
  - Search And Rescue Service (SAR)
    - Broadcast the alert messages received from distress emitting beacons on a dedicated channel (1544-1545 MHz)

GALILEO Architecture

- Global component:
  - Constellation:
    - 27 satellites + 3 active spares, 23,222 km above Earth
    - 3 orbital planes, 56˚ inclination (9 operational SVs and 1 spare per plane)
  - Ground:
    - Two redundant GALILEO Control Centers (GCC)
    - A network of GALILEO Up-link Stations (GUS)
    - A network of GALILEO Sensors Stations (GSS)
    - A GALILEO Communication Network (GCN)

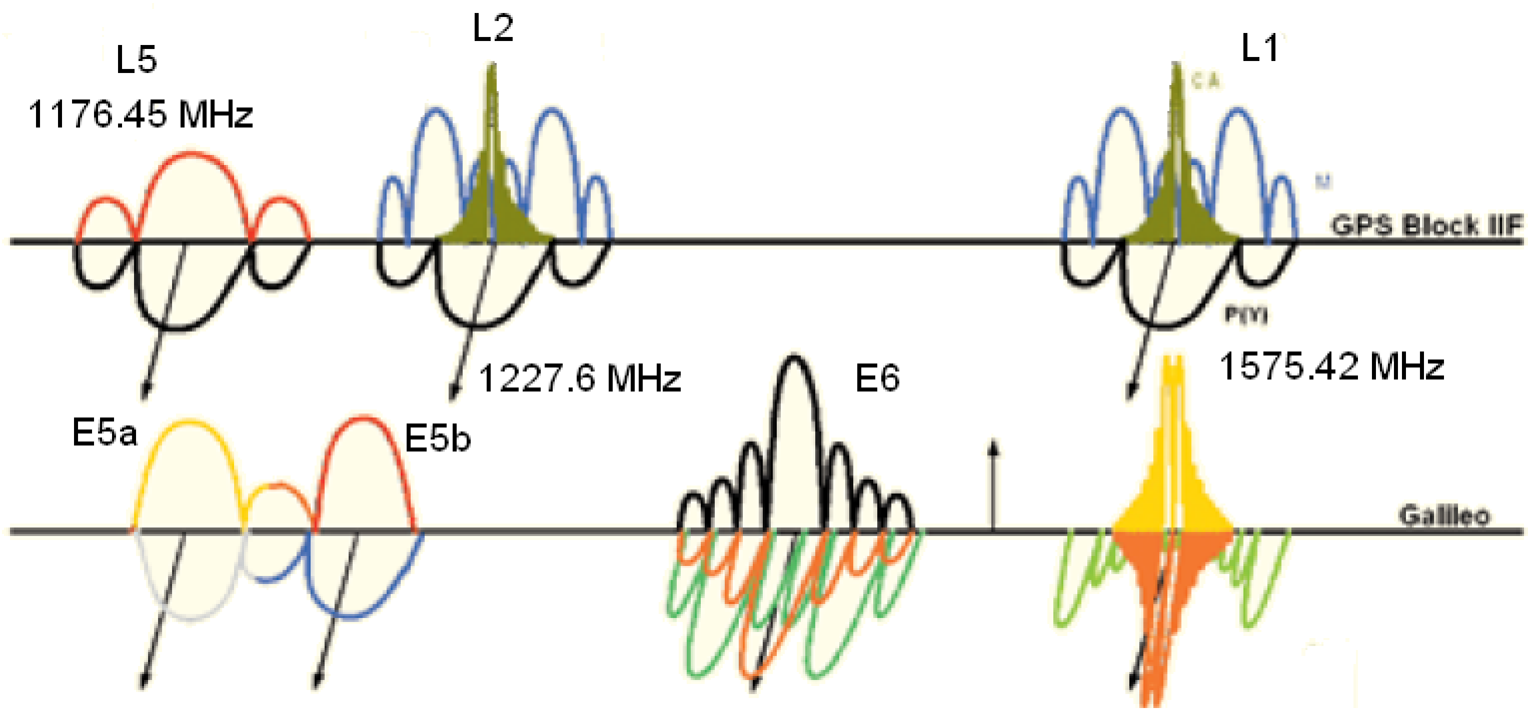


- Regional component:
  - To ‘personalize’ integrity in a specified region
- Local component:
  - To adapt to very specific environment (airports, ports, rails, etc…)
- User receivers and terminals:
  - Wide range of receivers dedicated to each services

Galileo Signals

Signal	Centre Frequency	Modulation Type	Bandwidth (MHz)	Chip Rate (MHz)	Spreading Codes	Code Length	Signal Component	Service Name
E1A	1,575.42	BOC(15,2.5)	15.345	2.5575	N/A	N/A	N/A	PRS
E1B	1,575.42	CBOC(6,1,1/11)	1.023	1.023	Random Codes	4092	Data	OS
E1C	1,575.42	CBOC(6,1,1/11)	1.023	1.023	Random Codes	4092	Pilot	OS
E6A	1278.75	BOC(15,2.5)	10.230	5.115	N/A	N/A	N/A	PRS
E6B	1278.75	BPSK(5)	10.230	5.115	Random Codes	5115	Data	CS
E6C	1278.75	BPSK(5)	10.230	5.115	Random Codes	5115	Pilot	CS
E5a-I	1176.45	AltBOC(15,10)	20.46	10.23	Gold Codes	10230	Data	OS
E5a-Q	1176.45	AltBOC(15,10)	20.46	10.23	Gold Codes	10230	Pilot	OS
E5b-I	1207.14	AltBOC(15,10)	20.46	10.23	Gold Codes	10230	Data	OS
E5b-Q	1207.14	AltBOC(15,10)	20.46	10.23	Gold Codes	10230	Pilot	OS

Section 1.7	Signal Structure
GPS - Galileo	



New signals and new modulations have been proposed in order to improve positioning accuracy and further develop GNSS services

From S. Lo, A. Chen, P. Enge, G. Gao, D. Akos, j-L Issler, L. Ries, T. Grelier and J. Dantepal, “GNSS Album Images and Spectral Signatures of the New GNSS Signals”, Inside GNSS, May/June 2006

BeiDou Navigation Satellite System (BDS)

- 27 Medium Earth Orbit (MEO) SVs
  - 21,500 km above Earth
  - Inclination: 55˚
- 3 Inclined Geosynchronous Satellite Orbit (IGSO) SVs
  - 35,786 above earth
  - 55° inclination to the equatorial plane
- 5 Geostationary Earth Orbit (GEO) SVs
  - 35,786 km above Earth
- First experimental SVs launched in 2000
  - BeiDou-1
- BeiDou -2 deployment until 2020
- ICD 1.0 Released Dec 2012 (http://en.beidou.gov.cn/)

A Note on Orbits

- A geostationary orbit is an orbit where the satellite is directly above the equator. With this orbit the satellite is always directly above the same spot on the planet.
- A geosynchronous orbit means that the orbital period is the same as the earth, but due to its inclination, the satellite will move in a figure 8 pattern over the same spot on the planet.

Overview

- Status as of Dec 2012
  - 5 GEO, 4 MEO and 5 IGSO
- Signal structure is CDMA
- Coordinate Frame
  - China Geodetic Coordinate System 2000 (CGCS2000)
- Time Reference
  - BeiDou navigation satellite system Time (BDT)
  - BDT was synchronized at 00:00:00 on January 1, 2006 of Coordinated Universal Time (UTC)
  - Leap seconds are broadcast with in the message
  - Within 100 nanoseconds of UTC (modulo 1 second)
- Orbital Parameters
  - Ephemeris with perturbation parameters
  - 1 hour update rate
- Minimum Power
  - -163 dBW

Compass/Beidou Signals

Signal	Centre Frequency	Modulation Type	Bandwidth (MHz)	Chip Rate (MHz)	Signal Component	Service Name
B1-I	1,561.098	QPSK	4.092	2.046	Data	OS
B1-Q	1,561.098	QPSK	4.092	2.046	Data	AS
B1-2	1,589.742	QPSK	4.092	2.046	Data	AS
B2-I	1207.14	QPSK	24	10.23	Data	OS
B2-Q	1207.14	QPSK	24	10.23	Data	AS
B3	1268.52	QPSK	24	10.23	Data	AS
B1-BOC	1575.42	CBOC(6,1,1/11)	16.368	1.023	Data	OS
B2-BOC	1207.14	BOC(10,5)	30.69	5.115	Data	OS
B3-BOC	1268.52	BOC(15,2.5)	35.805	2.5575	Data	AS
L5	1176.45	QPSK	24	10.23	Data	OS

China Satellite Navigation Project Center (CSNPC) (2008), Overview of Compass/ Beidou Navigation Satellite System {http://www.unoosa.org/pdf/icg/2008/expert/2-1a.pdf}

Section 1.9	GLONASS

Overview

- GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sustena)
- 24 Medium Earth Orbit (MEO) SVs (+3 spares)
  - 19,100 km above Earth
  - Period of 11 hours 15 minutes
  - 3 orbital planes 120˚ apart
  - Inclination: 64.8˚
- First satellite launch in 1982
- GLONASS-**M** (modernized) began in 2003
  - Better clocks (10^{-13} per day)
  - Better attitude control systems on satellite
  - Longer lifetime of 7 years
  - L2 C/A code added
  - Enhanced navigation message
- GLONASS **K1** and **K2** (further modernization) began in 2011
  - Further clock improvements (10^{-14} per day)
  - Longer lifetime of 10-12 years
  - Possible to launch 6 at a time with smaller size (half that of GLONASS-M)
  - 2 Satellites to transmit differential corrections
  - Inter-satellite navigation links (continued from GLONASS-M)

Overview

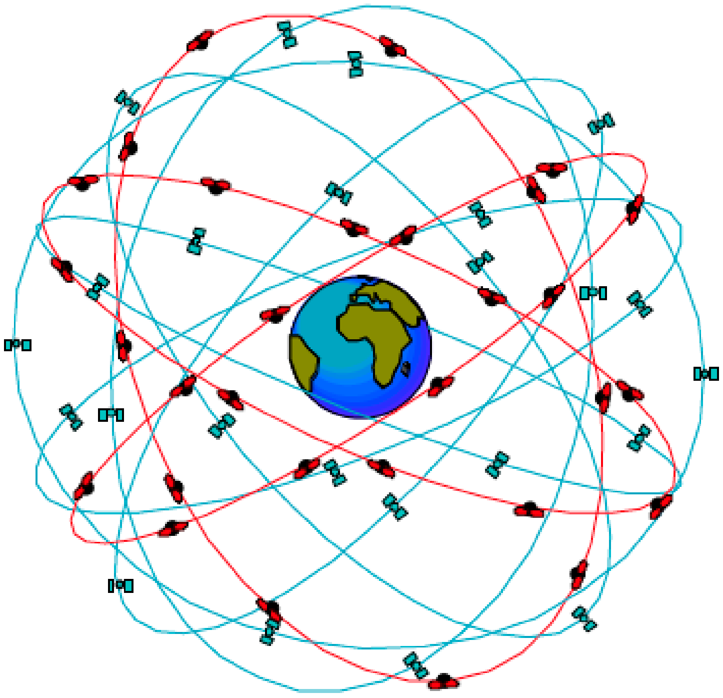
- Status as of July, 2013
  - 24 GLONASS-M satellites (1 GLONASS-K satellite under testing)
- Signal structure is FDMA
  - Each satellite is allocated a channel number
  - L1:1602 + 0.5625*k MHz
  - L2: 1246 + 0.4375*k MHz
  - FDMA reduces cross-correlation of short ranging codes, but requires more complex front ends
- Coordinate Frame
  - Earth Parameter System 1990 (PZ-90.02)
- Time Reference
  - GLONASS time
- Orbital Parameters
  - Epoch by epoch based satellite coordinates and velocities
  - Compute specific satellite PVT using Runge Kutta Method
    - Good Reference: Stewart & Tsakiri (1998) GLONASS Broadcast Orbit Computation. GPS Solutions.
- Minimum Power
  - -161 dBW
- http://glonass-iac.ru/en/

Overview

Signal	Band and Frequency Range (MHz)	Modulation and Chipping Rate (MChip/s)	Navigation Message Rate	Minimum Received Signal Power (dBW)	Satellite Blocks
C/A	L1:1592.95-1613.86	BPSK 0.511	50	-161	All
P Code	L1:1592.95-1613.86	BPSK 5.11	50	-161	All
C/A	L2: 1237.83-1256.36	BPSK 0.511	50	-167	GLONASS -M Onward
P Code	L2: 1237.83-1256.36	BPSK 5.11	50	-167	GLONASS -M Onward
L3	1190.5-1212.0	BPSK 4.095			GLONASS -K Onward

Better Performance and Opportunities

- A geometry rich environment
- Better accuracy availability, continuity and reliability for outdoor and <u>indoor</u> applications
- New applications
- What are the commercial and research opportunities?



Some GNSS Information Sources

[1] - Col. P. F. Hoene, JPO, IEEE PLANS, San Diego, March 14, 2000.

[2] - The Global Positioning System – A Shared National Asset. National Research Council, Washington, D.C., May 1995.

[3] - Shaw, M., K. Sandhoo, and D. Turner (2000), Modernization of the Global Positioning System, GPS World, September, pp. 36-44.

[4] - McDonald, Keith (2001) The Future of GNSS: New Capabilities, Performances and Issues, Proceedings of KIS01, Dept of Geomatics Engineering, Univ. of Calgary.

[5] - Fontana, R., W. Cheung and T. Stansell (2001) The Modernized L2 Civil Signal – Leaping Forward in the 21st Century. GPS World, September 2001 Issue.

[6] R.D. Fontana et al (2001) The New L2 Civil Signal – Proceedings of GPS01 conference, ION. (www.navcen.uscg.gov)

[7] - Creel, T., A. J. Dorsey, P. J. Mendicki, J. Little, R. G. Mach, and B. Renfro (2006) "New, Improved GPS," in GPS World, Vol 17, No 3, March, Questex Media Group Inc., Newton MA

More GPS current info: www.navcen.uscg.gov/navinfo/Gps

National Space-Based Positioning, Navigation, and Timing (PNT) ExecutiveCommittee (www.PNT.gov). The latter replaces the IGEB (Interagency GPS Executive Board)