The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2025-45

Satellite Navigation Science and Technology for Africa

23 March - 9 April, 2009

Satellite Navigation

MISRA Pratap

The MITRE Corporation
202 Burlington Rd. / Rte 62
Bedford MA 01730-1420
U.S.A.

Satellite Navigation Science and Technology for Africa

The Abdus Salam International Center for Theoretical Physics, Trieste, Italy

23 March – 9 April 2009

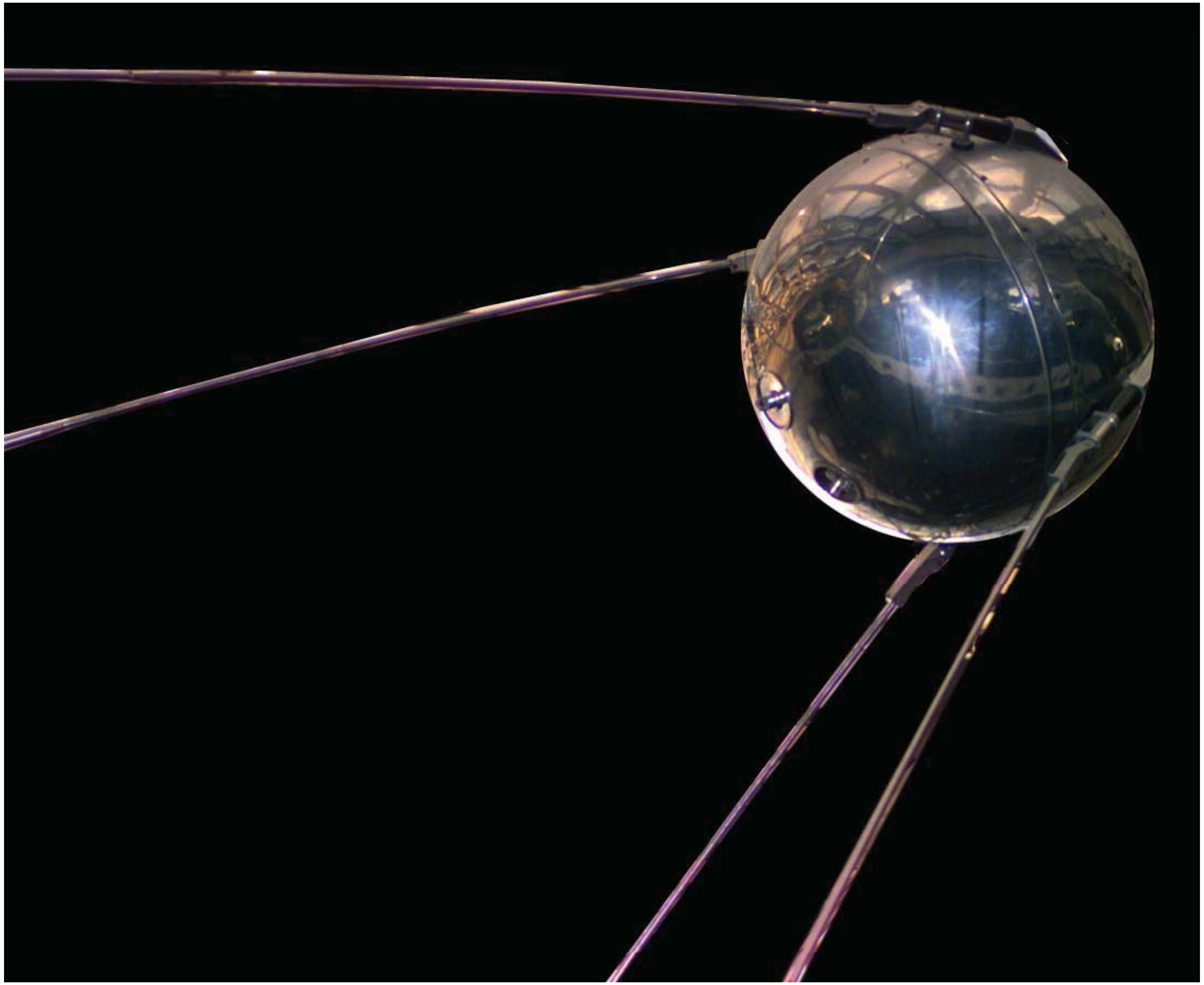
GPS Satellite (Block IIF)

An Overview of Satellite Navigation

Pratap Misra

Objectives

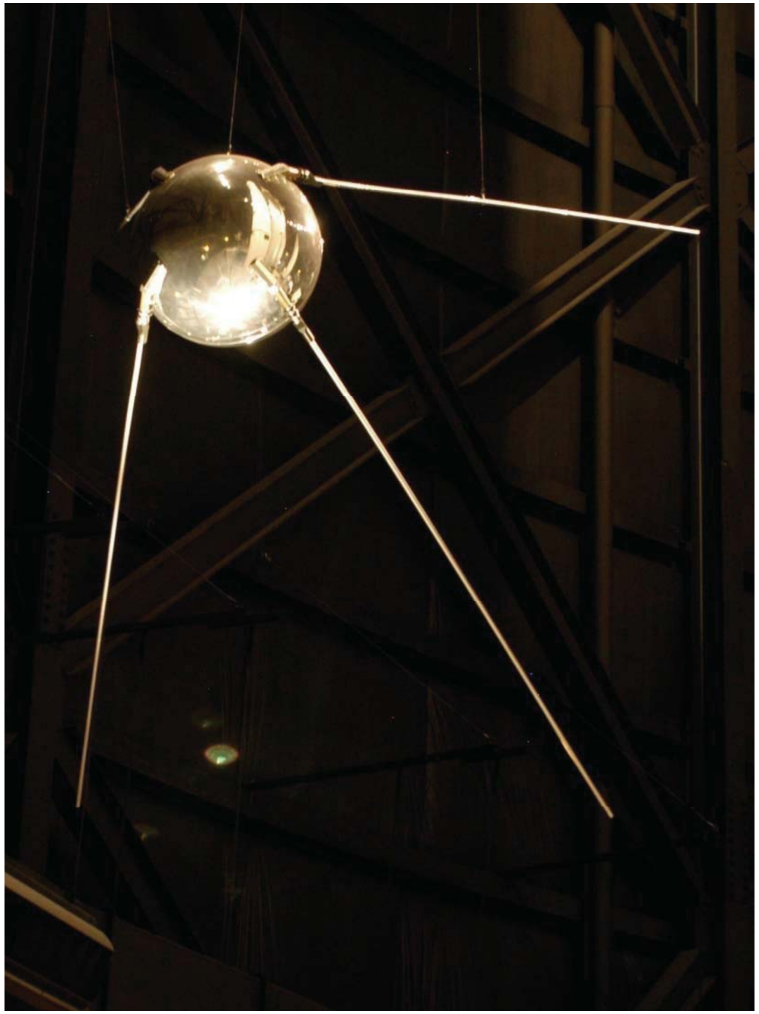
- To convey:
  - A broad understanding of the scientific and engineering principles of satellite navigation
  - The rudiments of GPS:
    - System
    - Signals and measurements
    - Performance
  - An outline of global navigation satellite systems under development: GLONASS, Galileo, Beidou
- Comprehensive discussions of these topics (and more) to follow later this week



?

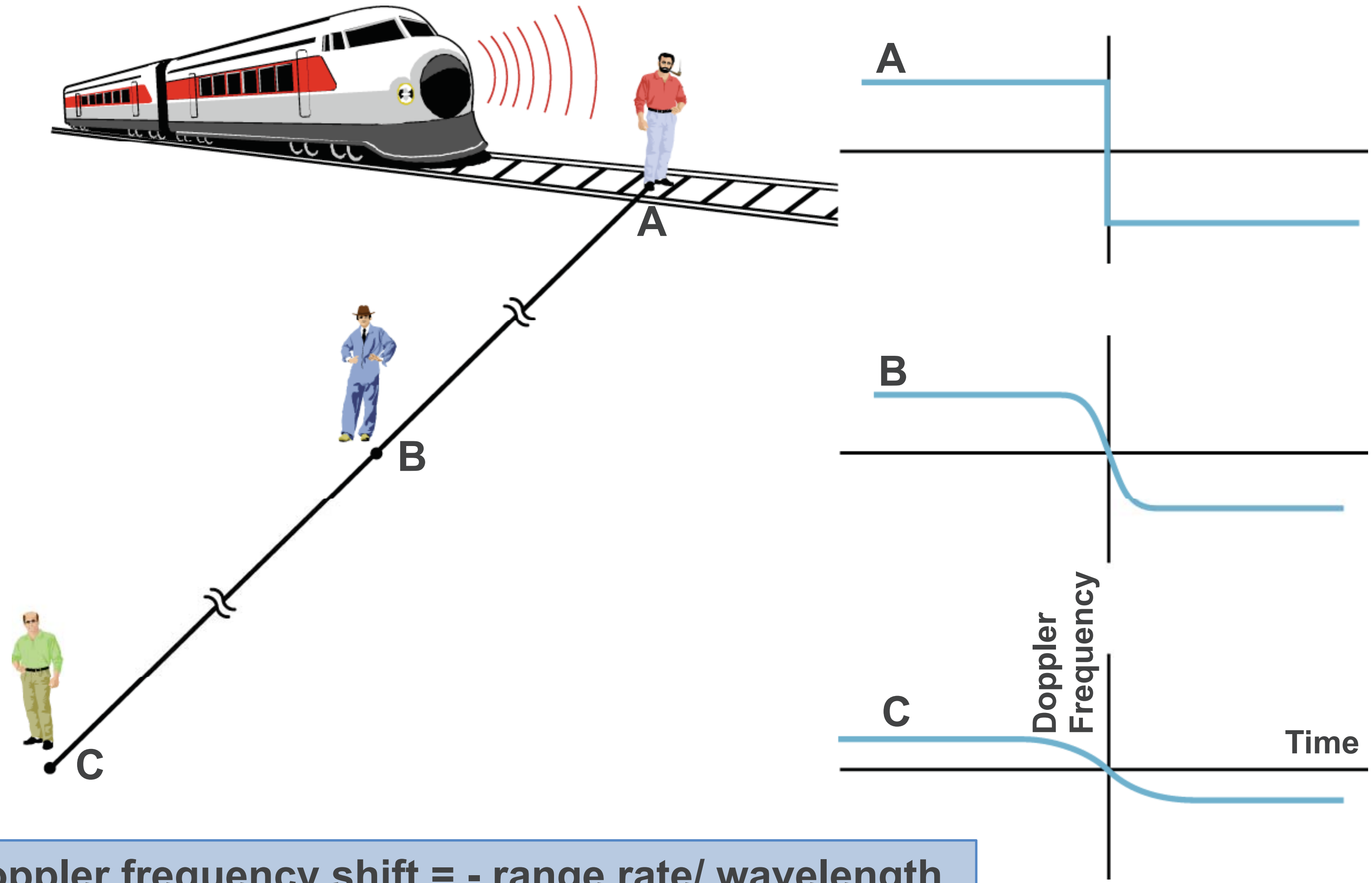
Простейший Спутник-1

- Space age began with the launch of Sputnik I by the Soviet Union on 4 October 1957
- ‘Beeps’ heard on short-wave radios tuned to 20 MHz or 40 MHz, Doppler shifted as the satellite moved in the sky*
- Within days, the idea of using radio signals from space for positioning on the earth was born



*http://history.nasa.gov/sputnik

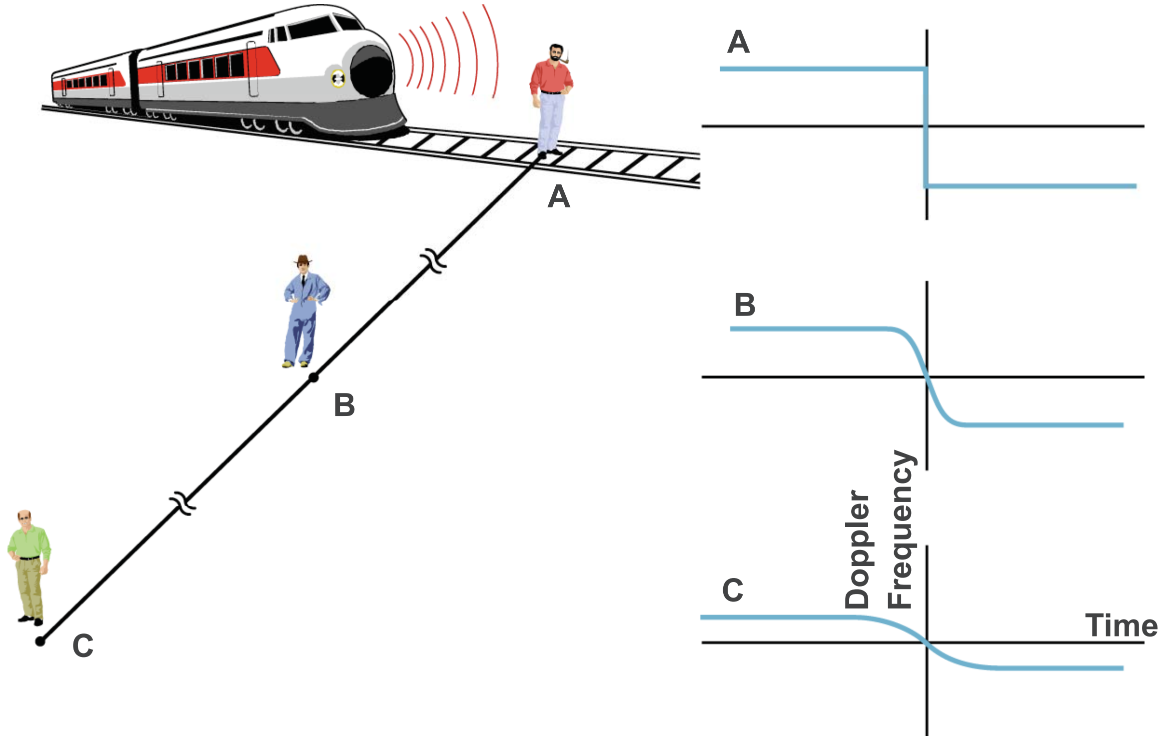
Doppler Effect



Doppler frequency shift = - range rate/ wavelength

Doppler Positioning

A Conceptual Exercise

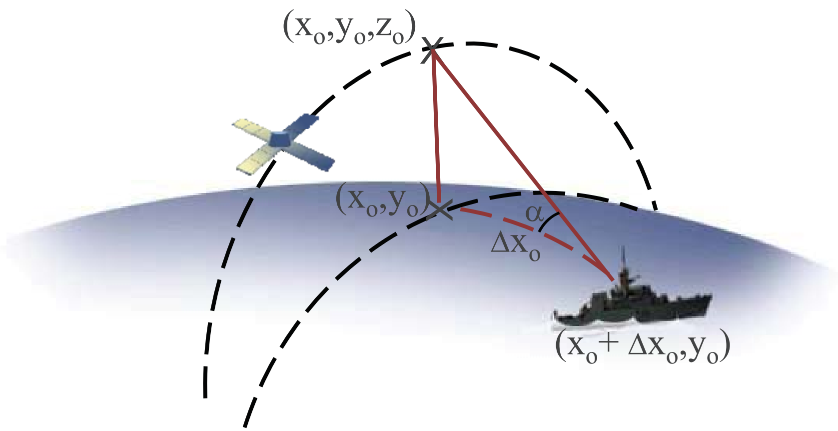


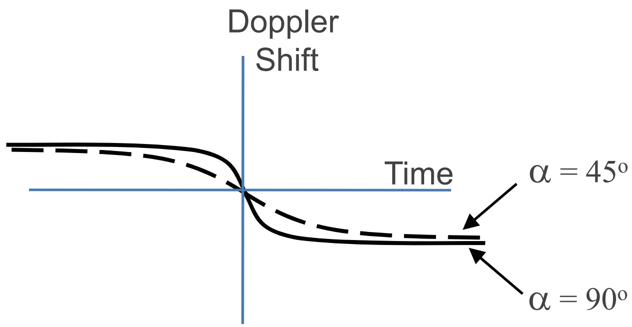
- Record time when Doppler shift went through zero
- Along-track position
  - From train's schedule
  - Error sources: Watch off, train off schedule
- Cross-track position
  - From Doppler profile
  - Ambiguity: Which side of the track?

Doppler frequency shift = - range rate/ wavelength

A Global Satellite Navigation System based on
Doppler Positioning

- **Satellite transmits**
  - Frequency-stable signal
  - Time, orbital parameters, clock parameters
- **Receiver measures Doppler frequencies and records transmitted data for an entire pass**
  - Determine coordinates of the point on the ground track corresponding to the point of closest approach
  - Determine offset from the ground track
- **Error Sources**
  - Satellite clock frequency stability over 10-20 min
  - User velocity

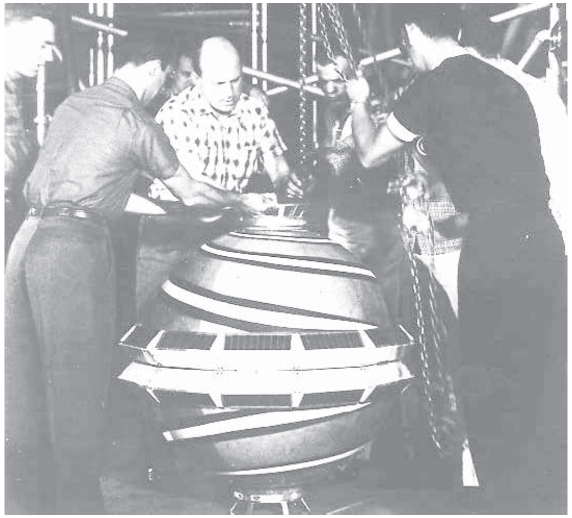


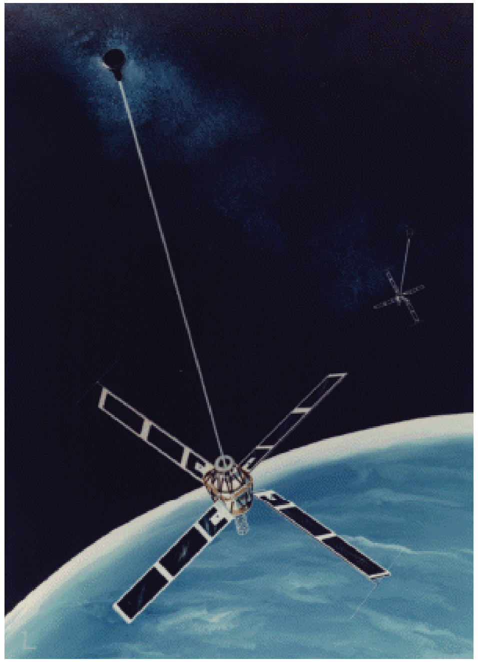


Adapted from *Marine Electronic Navigation* by Appleyard et al.

Transit (1964-1996)

- 4-7 satellites in 1100-km, circular, polar orbits
- One satellite in view at a time
- A satellite pass lasted 10-20 min; up to 100-min wait between passes
- Satellite weight: 50 Kg (160 Kg)
- Signals at 150 MHz & 400 MHz
- Signal power: 1 watt
- 2-D Positioning accuracy (for a stationary users): 25 m
- ~ 10,000 receiver sets in 1980, cost: ~$25,000





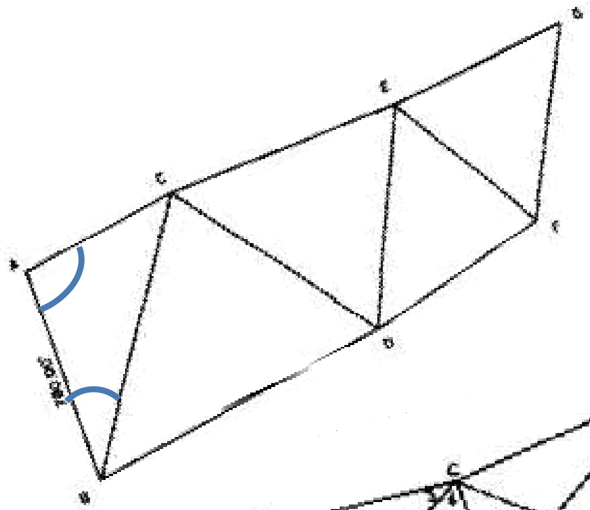
Satellite Navigation Overview

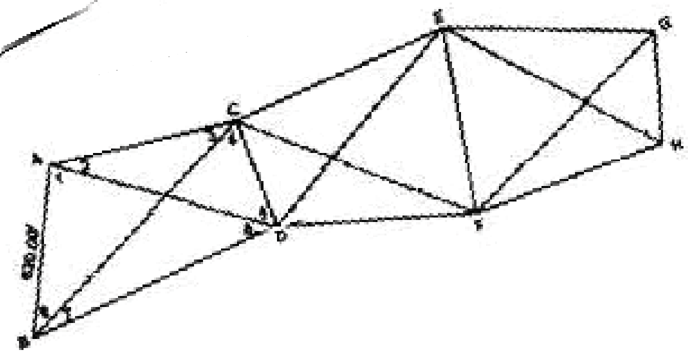
Outline

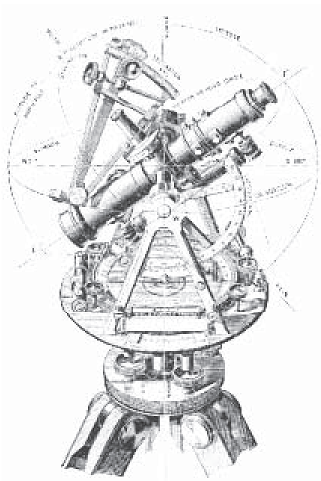
- Principles of Satellite Navigation
- GPS Overview: System, Signals and measurements, Performance
- Applications and Performance Metrics
- Potential Partners/Rivals: GLONASS, Galileo, BeiDou/Compass, …

Triangulation

Method of determining the position of a fixed point from the angles to it from two fixed reference points a known distance apart



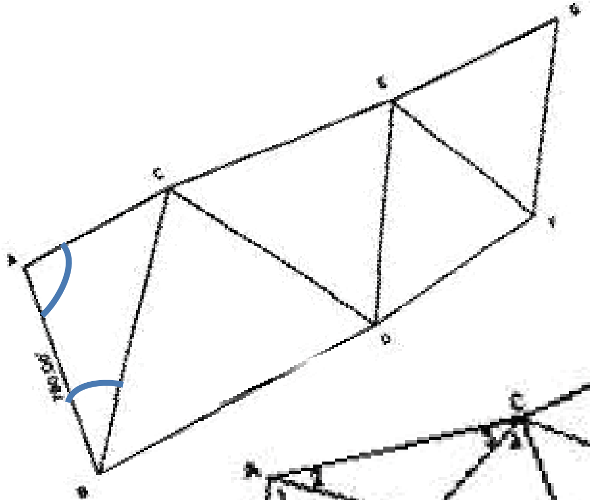


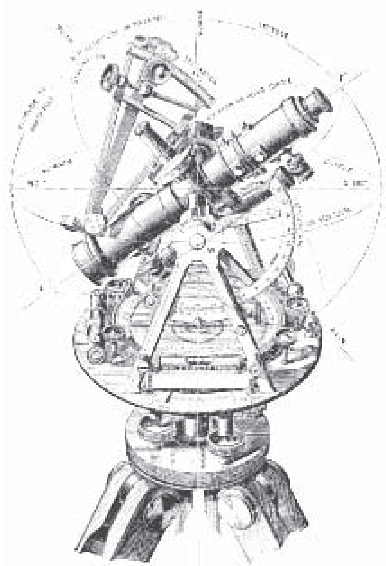


from *Trigonometry Surveying and Navigation* by G.A.Wentworth

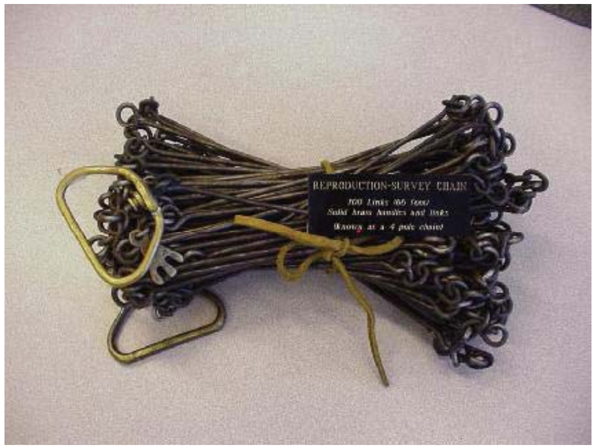
Triangulation

Method of determining the position of a fixed point from the angles to it from two fixed reference points a known distance apart





from *Trigonometry Surveying and Navigation* by G.A.Wentworth



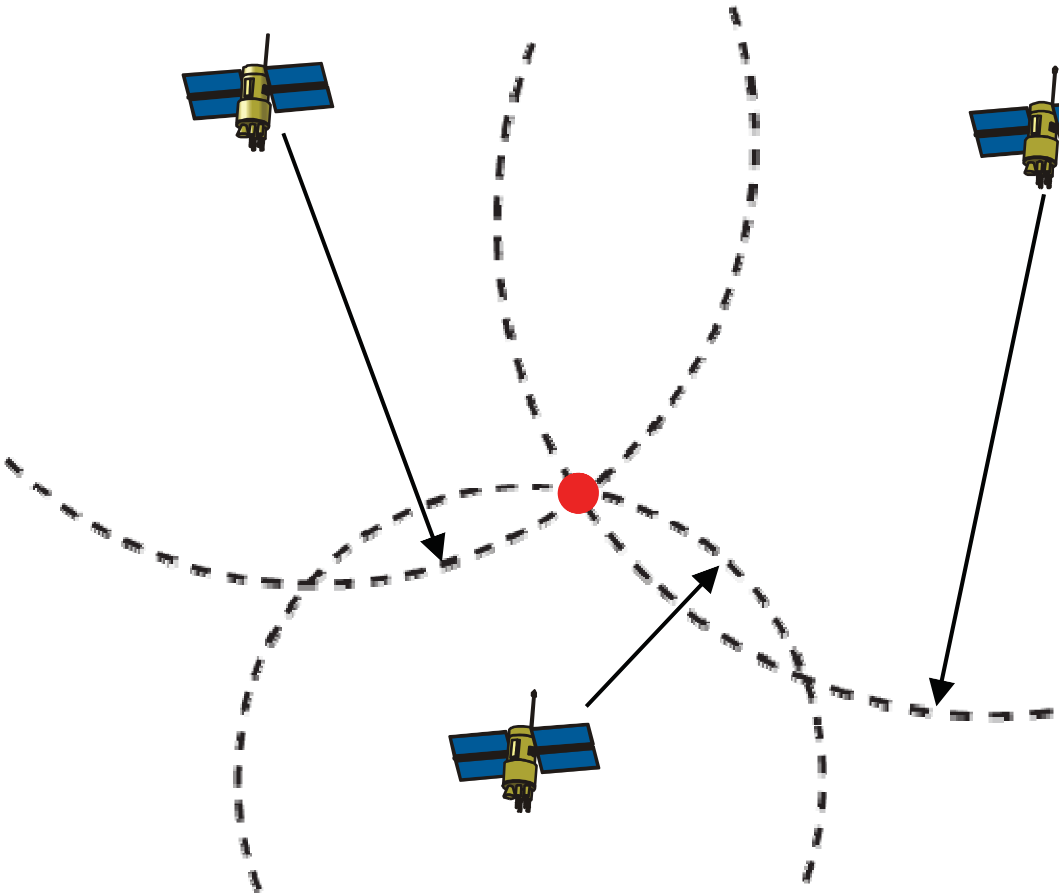
Surveyor's chain
from www.landsurveyinghistory.ab.ca

Trilateration

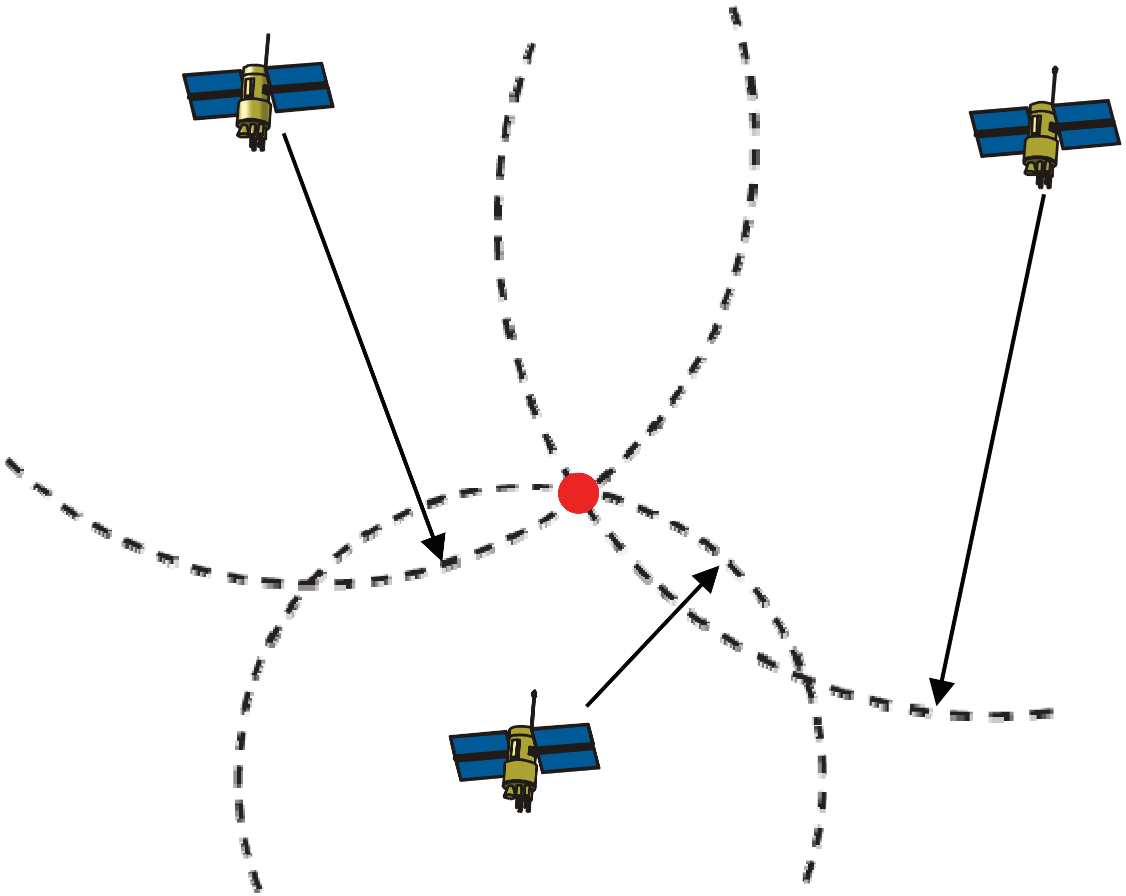
Measure lengths of the sides of a triangle rather than angles

A chain = 100 links = 66 feet long,
80 chains make a mile.
A "rod" or "pole" is 1/4 of a chain, or 16-1/2 feet long. Thus "40 rods" is 10 chains, or 1/8 of a mile.

2-D Trilateration



Trilateration

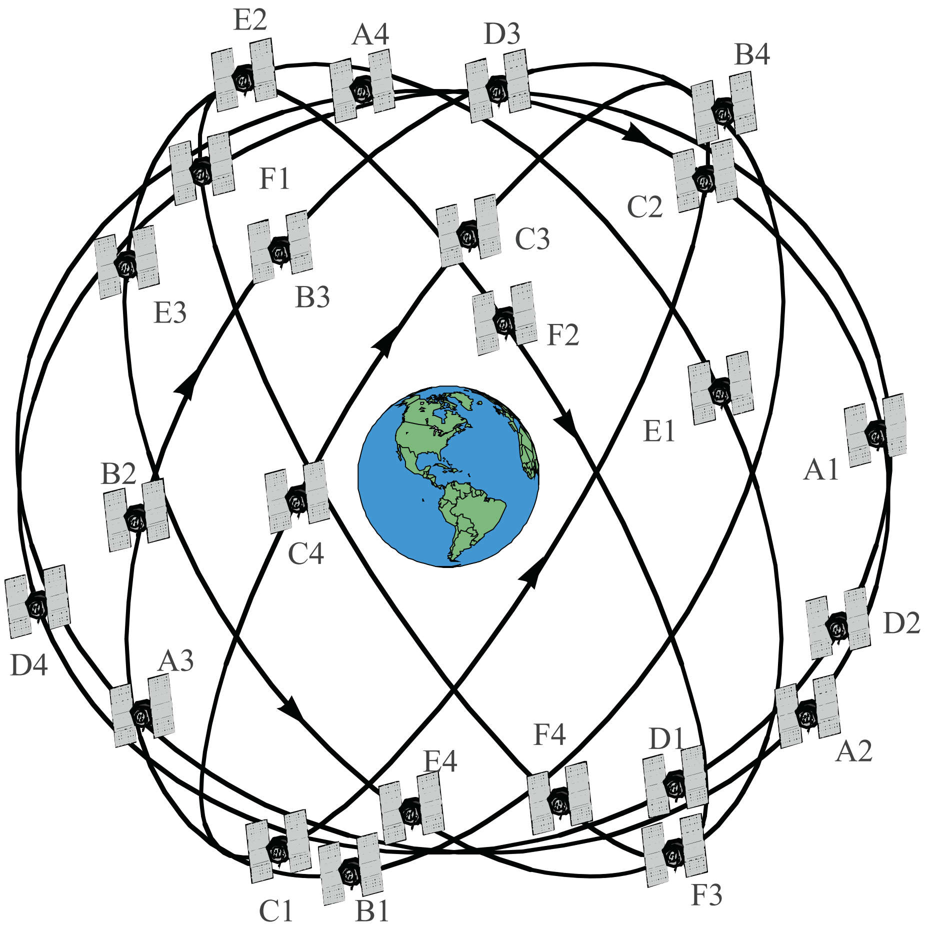


Satellite Navigation Enabling Technologies

- Stable space platforms with predictable orbits

GPS Baseline Satellite Constellation

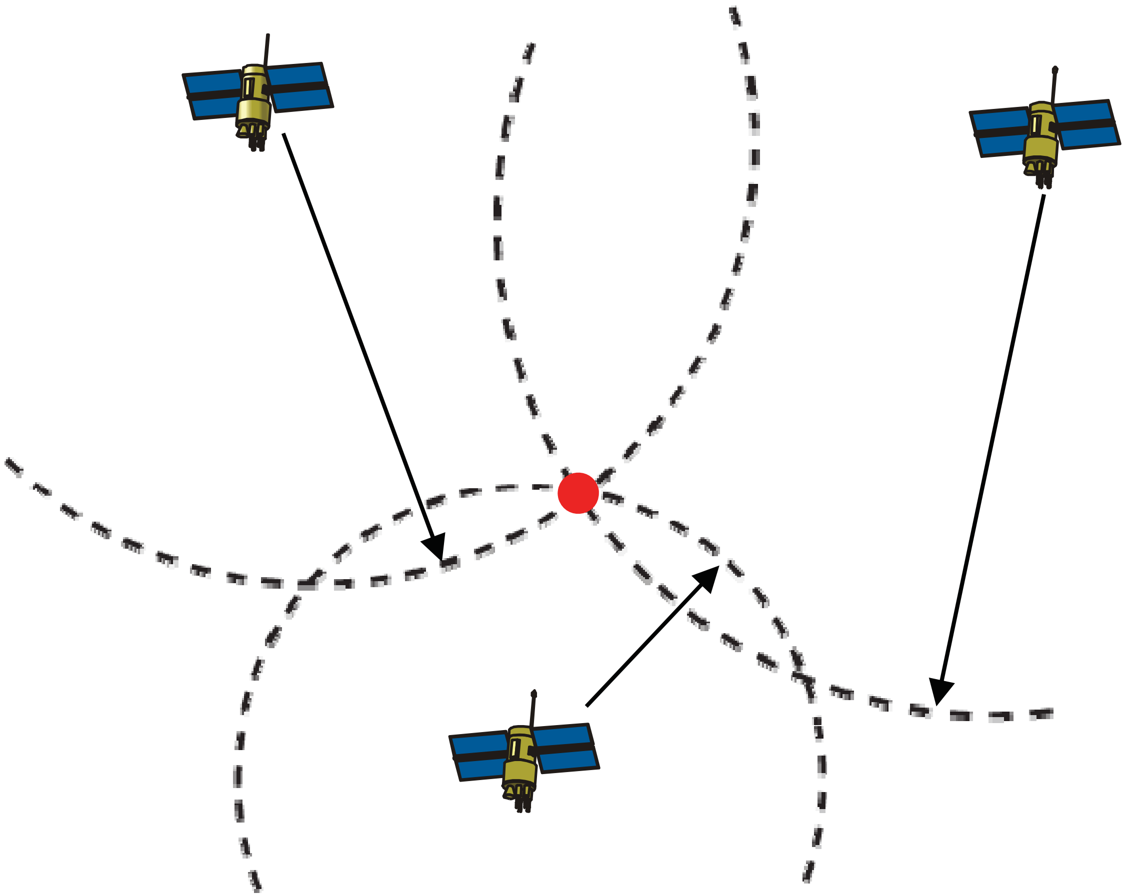
since 1980



- Satellites: 24
- Orbital planes: 6
- Inclination: 55 deg
- Altitude: 20,000 km
- Period: 11 h, 58 min

• Actual number of satellites has exceeded 24 since 1995, and is currently 29
• U.S. Government intends to maintain at least 22 satellites in their nominal slots

Trilateration

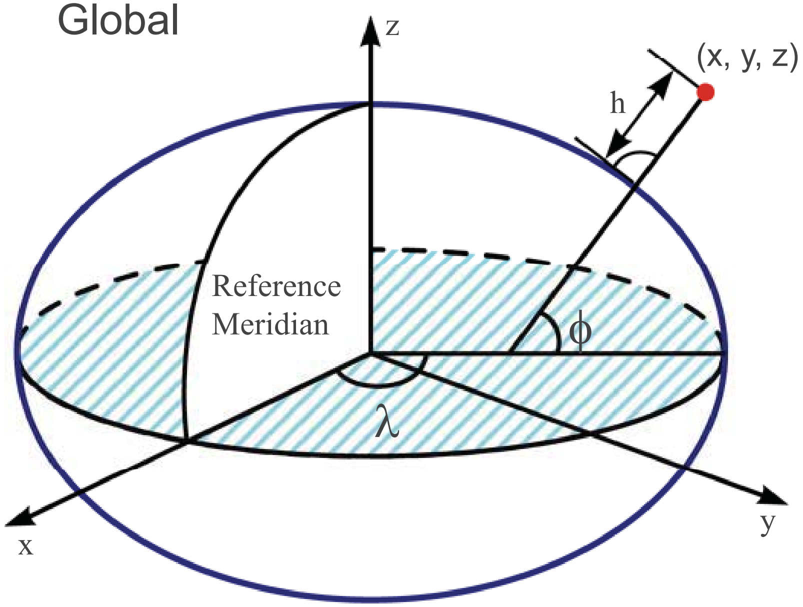


Satellite Navigation Enabling Technologies

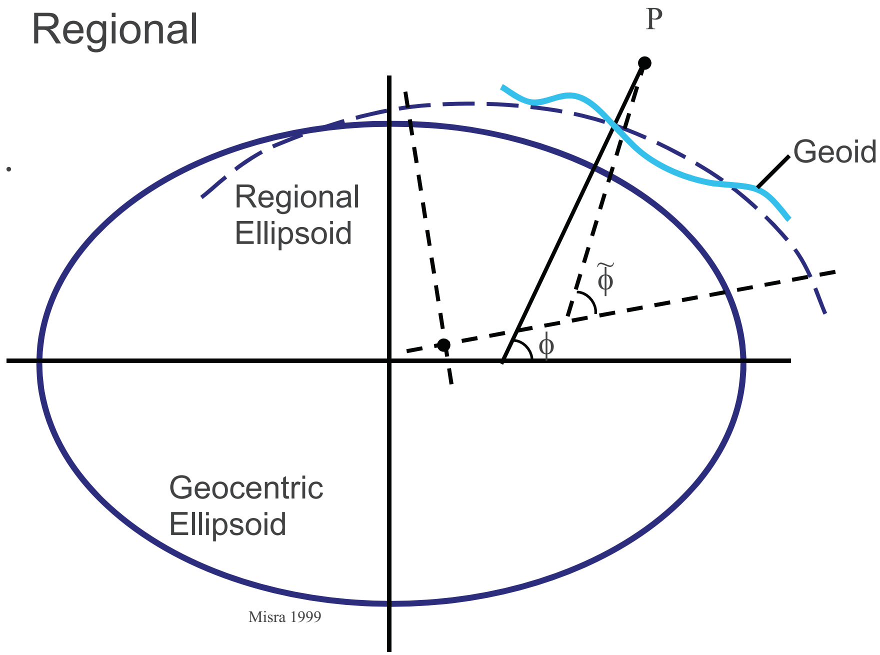
- Stable space platforms with predictable orbits
- Global coordinate frame (Earth-centered, Earth-fixed)

Global and Regional Coordinate Frames

Global



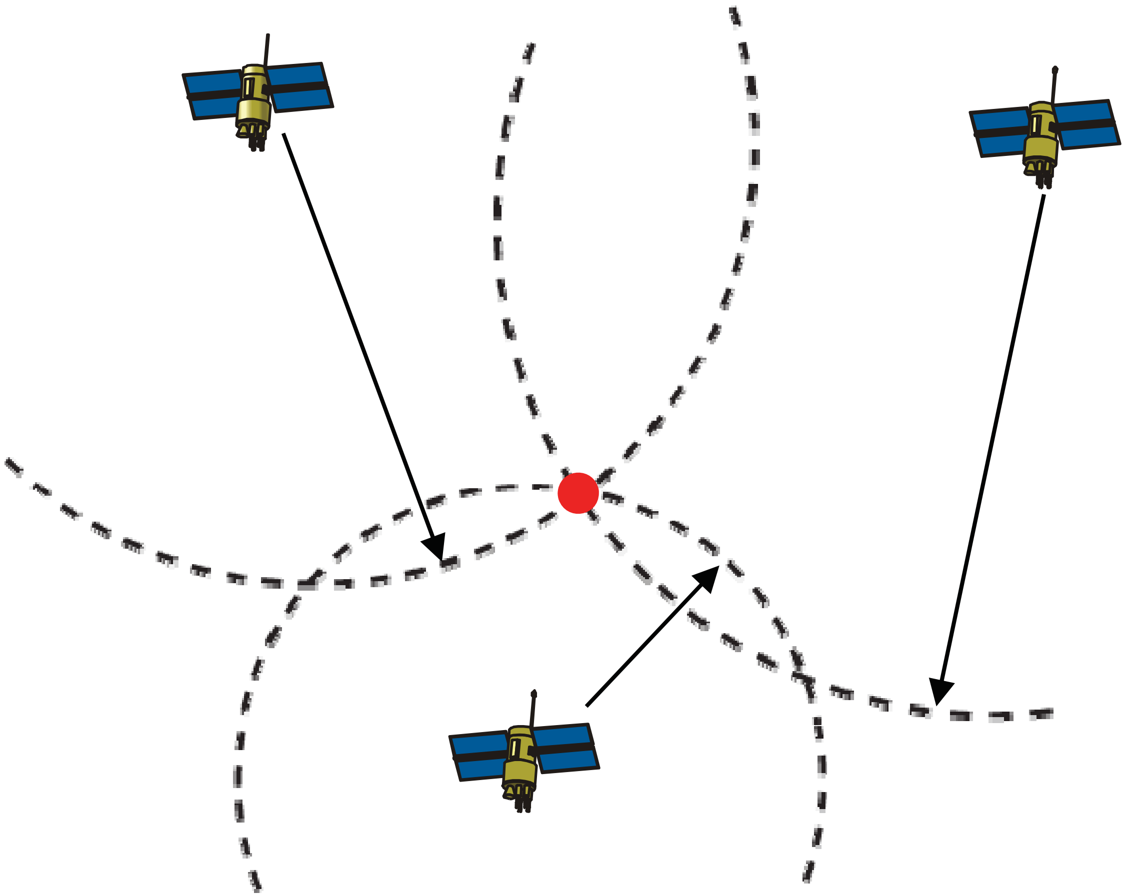
Regional



ϕ Geodetic latitude defined relative to a geocentric ellipsoid

$\tilde{\phi}$ Geodetic latitude defined relative to a regional ellipsoid

Trilateration



Satellite Navigation Enabling Technologies

- Stable space platforms with predictable orbits
- Global coordinate frame (Earth-centered, Earth-fixed)
- Ultra-stable clocks aboard satellites to transmit synchronized signals

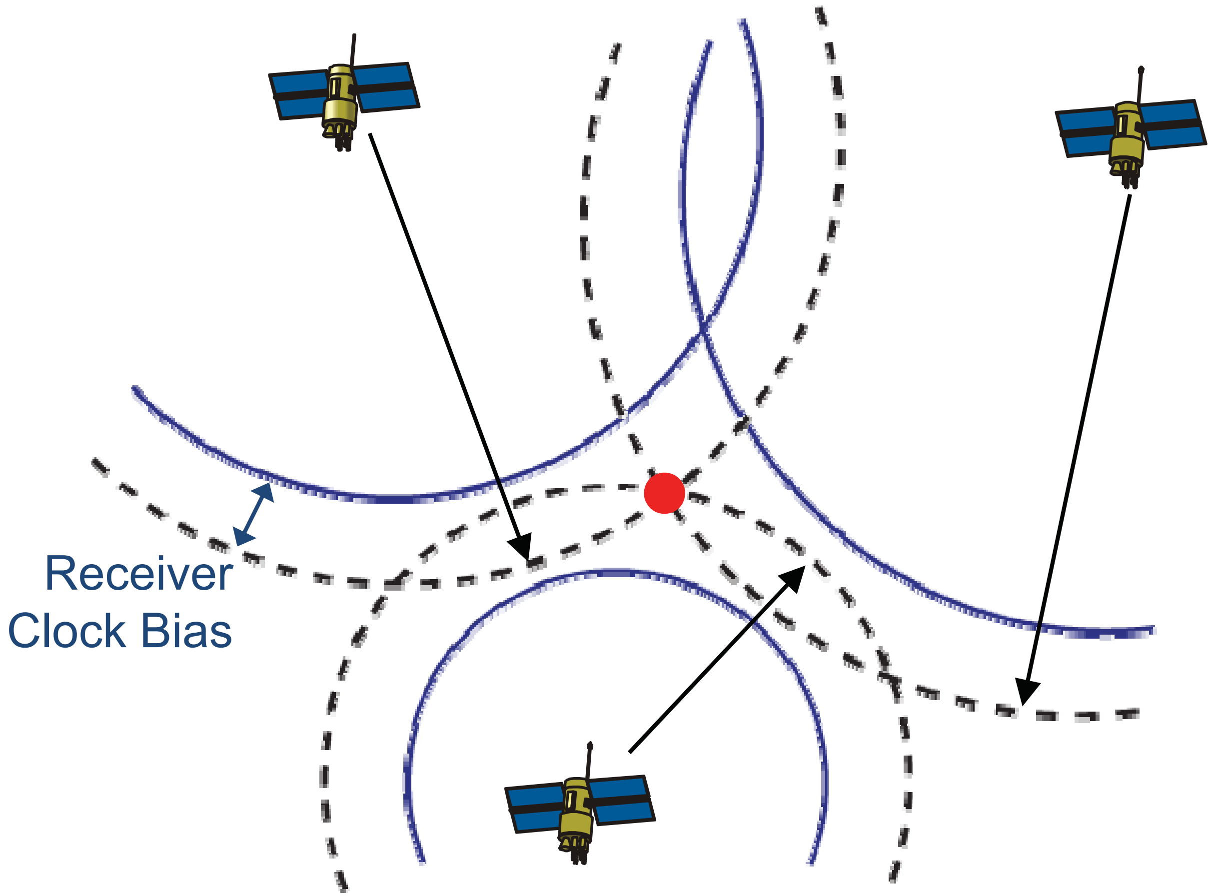
Frequency stability of 1 part in 10^{13} /day:

$$\frac{\Delta f}{f} = 10^{-13}$$

$$= -\frac{\text{Timekeeping error}}{\text{Time interval}}$$

Timekeeping error : ~10 ns/day

Trilateration

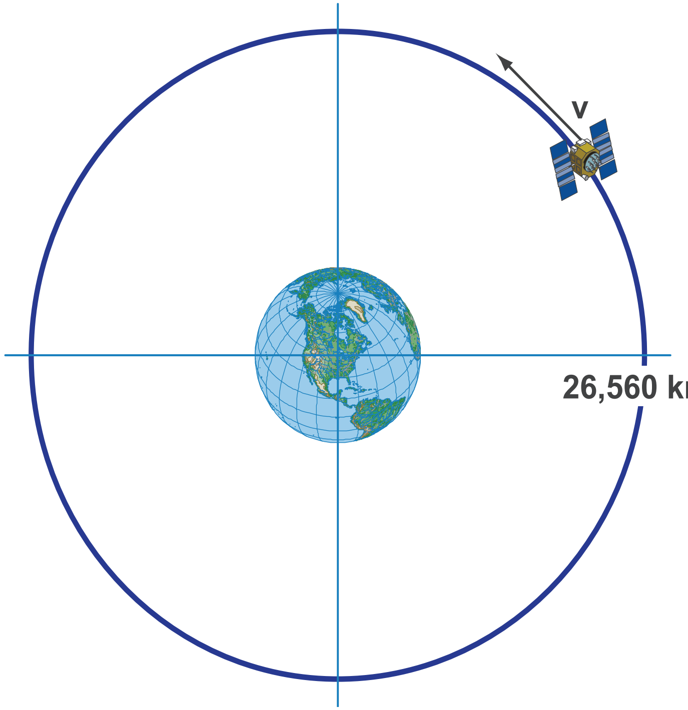


Satellite Navigation Enabling Technologies

- Stable space platforms with predictable orbits
- Global coordinate frame (Earth-centered, Earth-fixed)
- Ultra-stable clocks aboard satellites to transmit synchronized signals, but inexpensive clocks in receivers

Relativistic Effects: Circular 12-h Orbit

Atomic clock drift: $\frac{\Delta f}{f} \approx 10^{-13}$



- **Second-order Doppler shift (time dilation)**

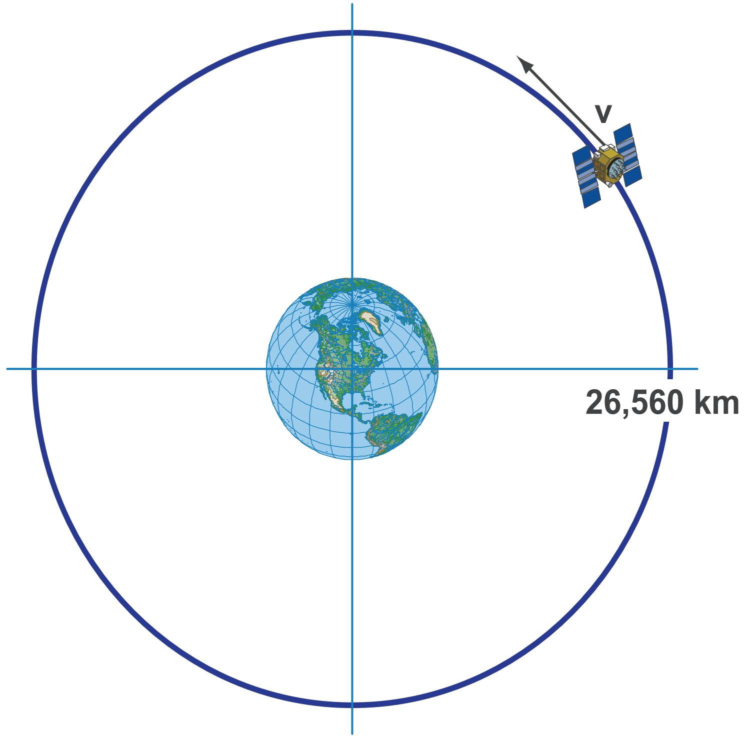
$$\frac{\Delta f}{f} = \frac{v^2}{2c^2} \approx 1\text{x } 10^{-10} \quad \text{(negative)}$$

- **Gravitational frequency shift**

$$\frac{\Delta f}{f} = \frac{\Delta\Phi}{c^2} \approx 5 \text{ x } 10^{-10} \quad \text{(positive)}$$

Relativistic Effects: Circular 12-h Orbit

Atomic clock drift: $\frac{\Delta f}{f} \approx 10^{-13}$



Combined effect accounted for by "factory offset" of satellite clock by

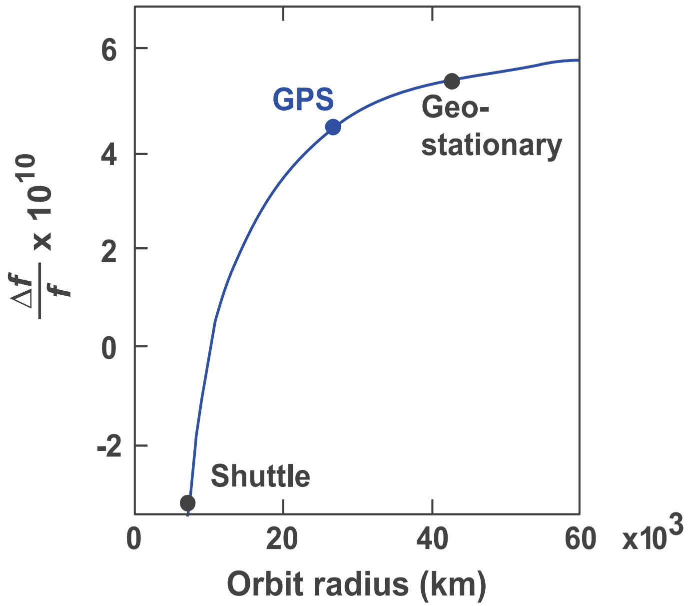
$$\frac{\Delta f}{f} = -4.4645 \times 10^{-10}$$

- Second-order Doppler shift (time dilation)

$$\frac{\Delta f}{f} = \frac{v^2}{2c^2} \approx 1\text{x } 10^{-10} \quad \text{(negative)}$$

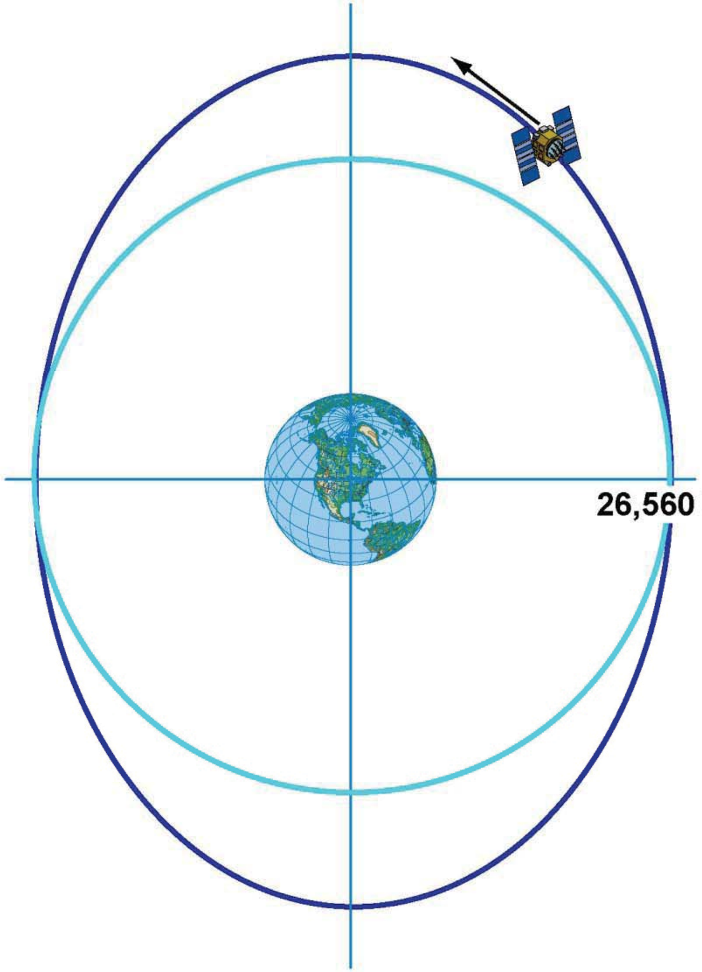
- Gravitational frequency shift

$$\frac{\Delta f}{f} = \frac{\Delta \Phi}{c^2} \approx 5 \text{ x } 10^{-10} \quad \text{(positive)}$$



PM112905U-p4

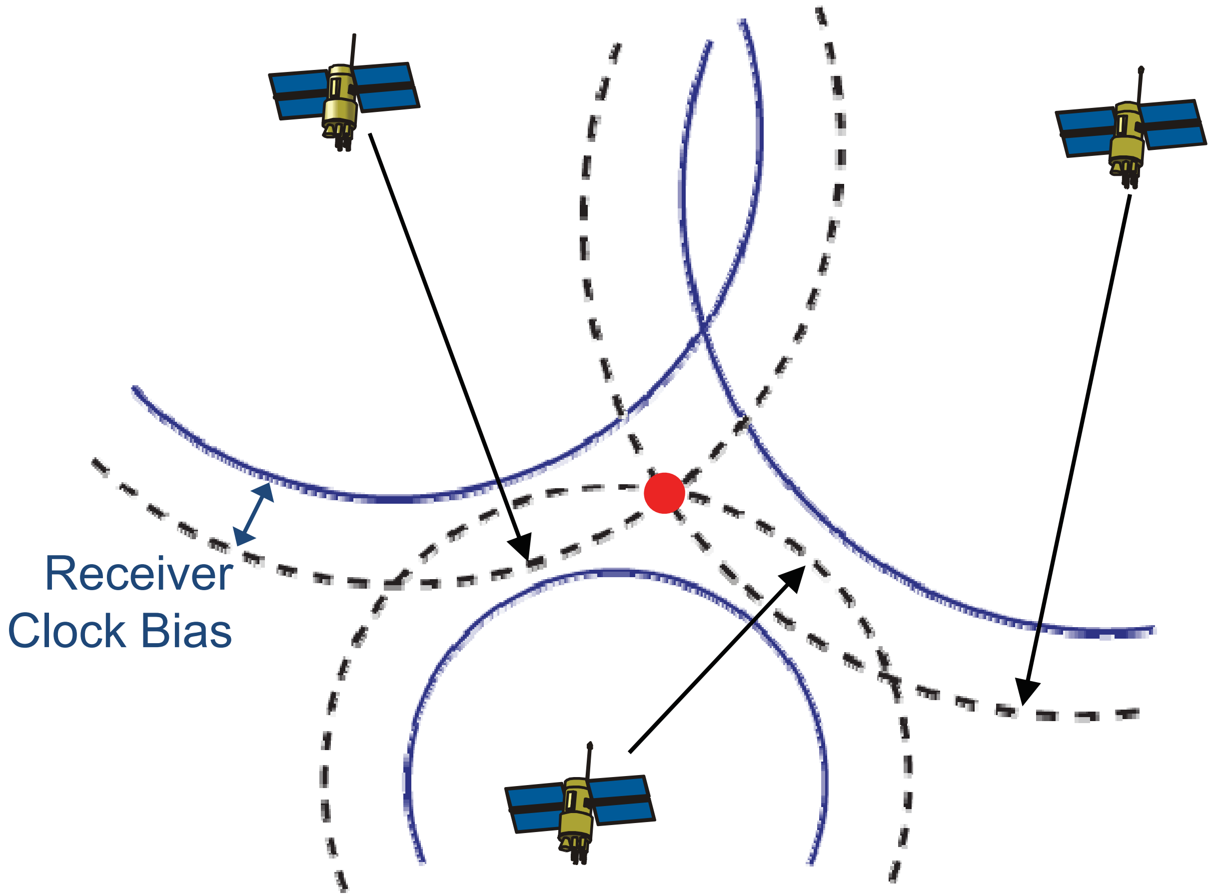
Relativistic Effects: Elliptical Orbit



- Eccentricity effect
  - Periodic shift of clock rate with 12-h period
  - 1% eccentricity: Periodic error with amplitude 28 ns in signal transit time (~10 m)
  - Accounted for in GPS receivers

- Smaller Effects, generally neglected but compensated for automatically in differential GPS
  - Sagnac effect
  - Shapiro delay
  - Nonspherical gravity potential
  - Tidel effects from sun and moon
  - Lense-Thirring drag

Trilateration



Satellite Navigation Enabling Technologies

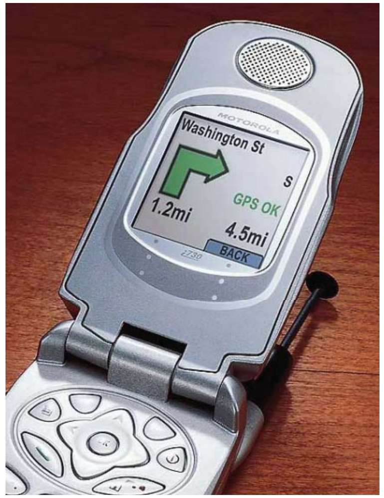
- Stable space platforms with predictable orbits
- Global coordinate frame (Earth-centered, Earth-fixed)
- Ultra-stable clocks aboard satellites to transmit synchronized signals, but inexpensive clocks in receivers
- Integrated circuits: Compact, light, inexpensive receivers

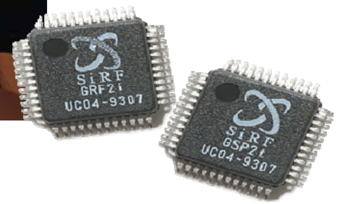
Evolution of GPS Receivers

from 10 Kg to 100 g, 100 watts to 1 watt, $ 100k to $ 100

Early 1980s

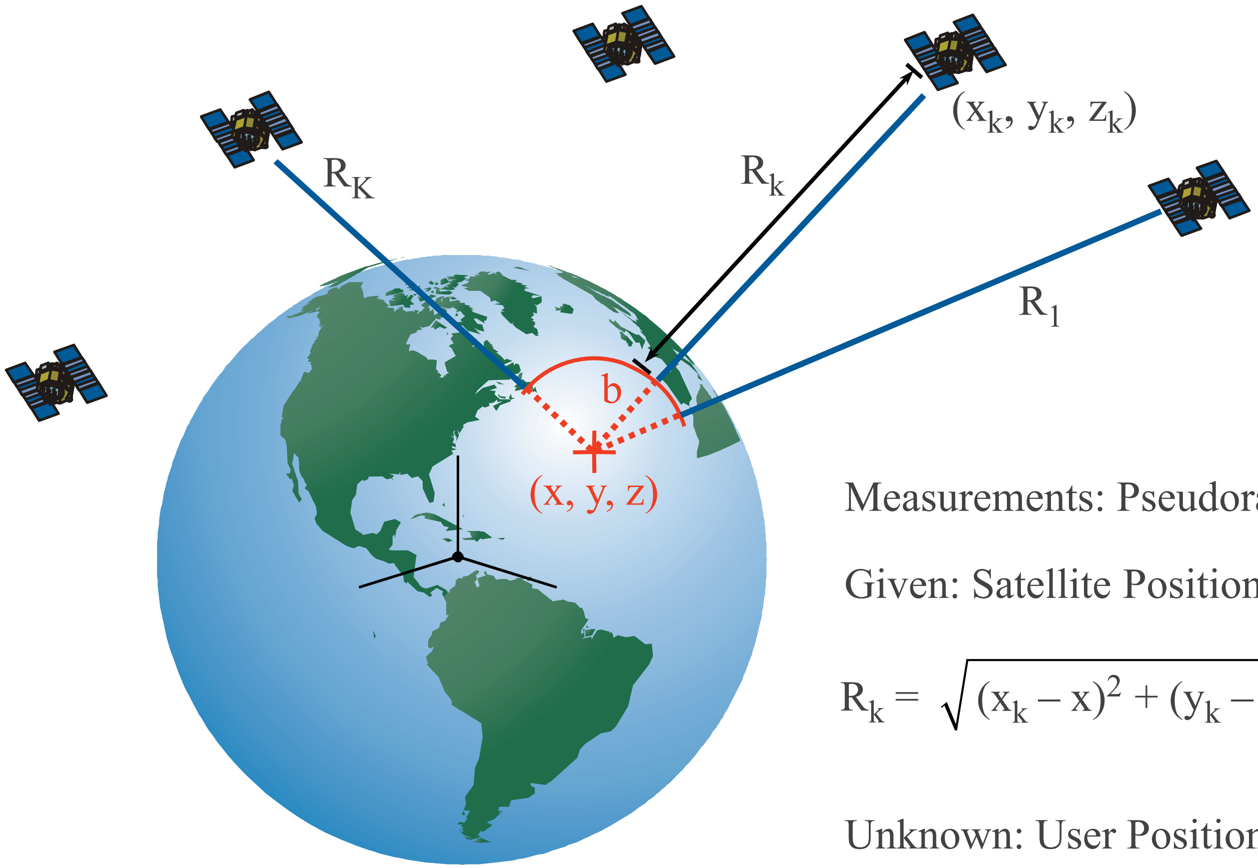
2005





Satellite Navigation

Position Estimation by Trilateration



Error Sources

- Ephemeris
- Satellite Clock
- Propagation through
  - Ionosphere
  - Troposphere
- Multipath
- Receiver Noise

Measurements: Pseudoranges $\{R_k\}$

Given: Satellite Positions $\{(x_k, y_k, z_k)\}$

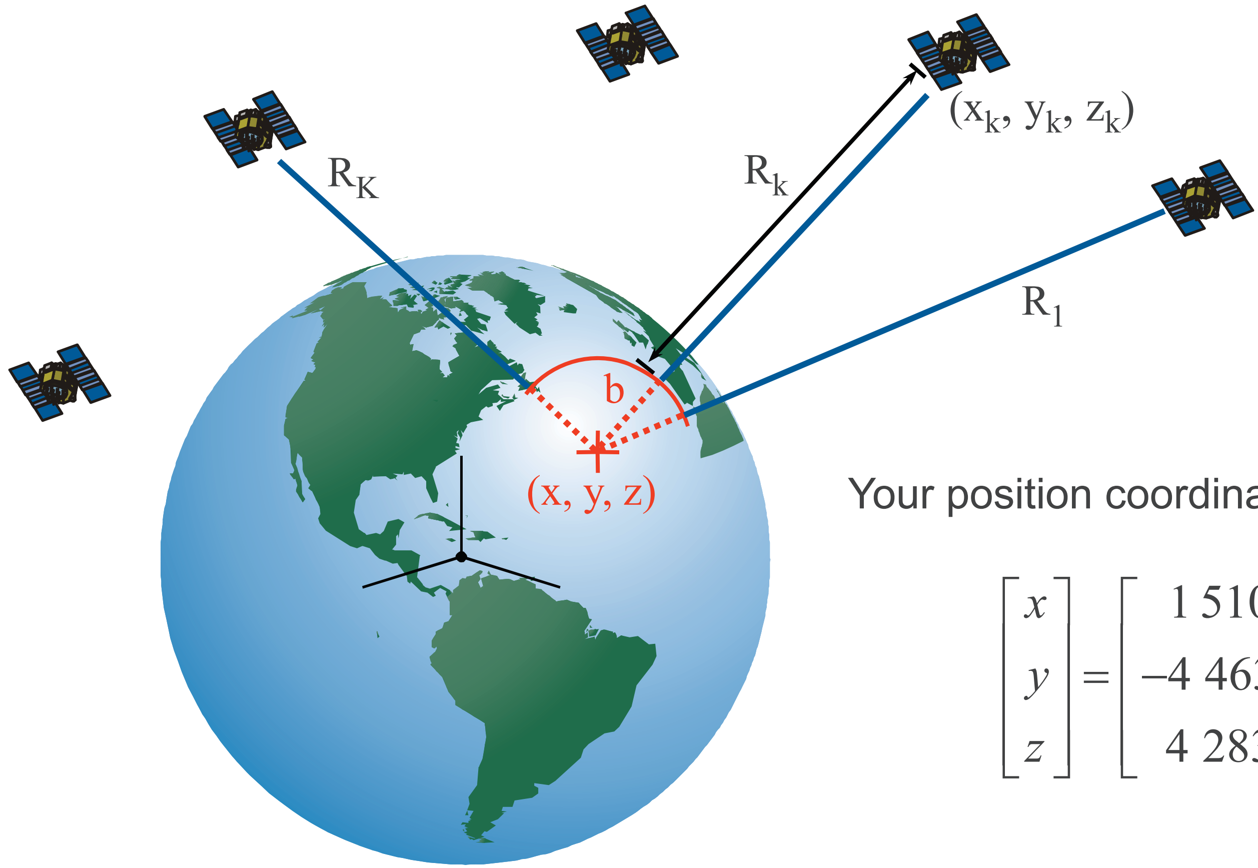
$$R_k = \sqrt{(x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2} - b, \quad k = 1, 2, \ldots, K$$

Unknown: User Position (x, y, z)

Receiver Clock Bias b

Satellite Navigation

Position Estimation by Trilateration



Your position coordinates are (in meters):

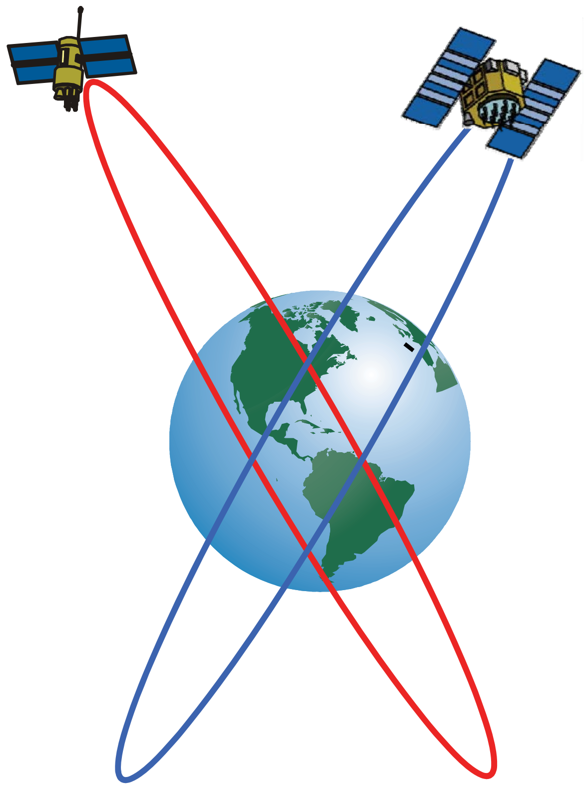
$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1\,510\,885.12 \\ -4\,463\,460.45 \\ 4\,283\,906.78 \end{bmatrix}$$

Satellite Navigation Objectives

- To provide estimates of
  - Position [~10 m]
  - Velocity [~0.1 m/s]
  - Time [~0.1 ms]

- Instantaneously
- Continuously
- Globally
- Cheaply, etc.

- To any number of users



Misra 1999

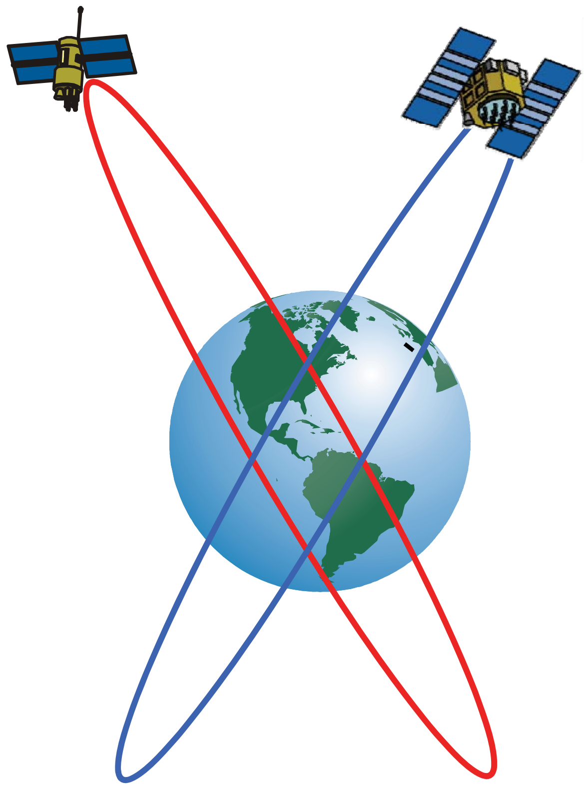
Satellite Navigation Objectives

- To provide estimates of
  - Position **[~10 m]**
  - Velocity **[~0.1 m/s]**
  - Time **[~0.1 μs]**

- Instantaneously,
  continuously,
  globally,
  cheaply, etc.

- To any number of users

Misra 1999



GPS Joint Program Office motto (Ca. 1975)

“The mission of this Program is: (1) Drop 5 bombs in the same hole, and (2) build a cheap set that navigates (< $10,000), and don’t you forget it!”

Satellite Navigation Overview

Outline

- Principles of Satellite Navigation
- GPS Overview: System, Signals and measurements, Performance
- Applications and Performance Metrics
- Potential Partners/Rivals: GLONASS, Galileo, BeiDou/Compass, …

GPS at a Glance

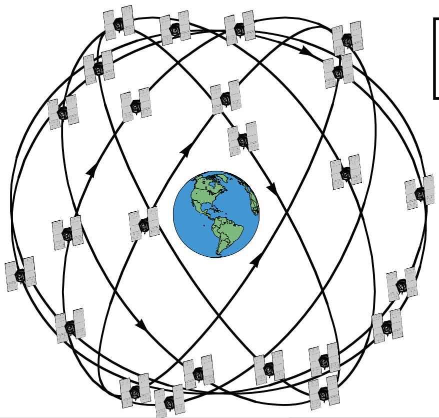
- Development began in early 1970s
  - First prototype satellite launched in 1978
  - Estimated number of receivers required: 27,000 (!)
  - Target cost of a receiver: $10,000 (!)
- Operational System
  - First operational satellite launched in 1989
  - System declared operational in 1995
- Expenditure
  - U.S. taxpayer investment (through 2007): $ 32b
  - Annual O&M costs: $ 1b
- Users: Millions
  - Most widely used military radio, albeit one way
  - Civil receivers manufactured annually: > 1 million
- Annual commerce in GPS products & services > $10 b

U.S. Policy on GPS

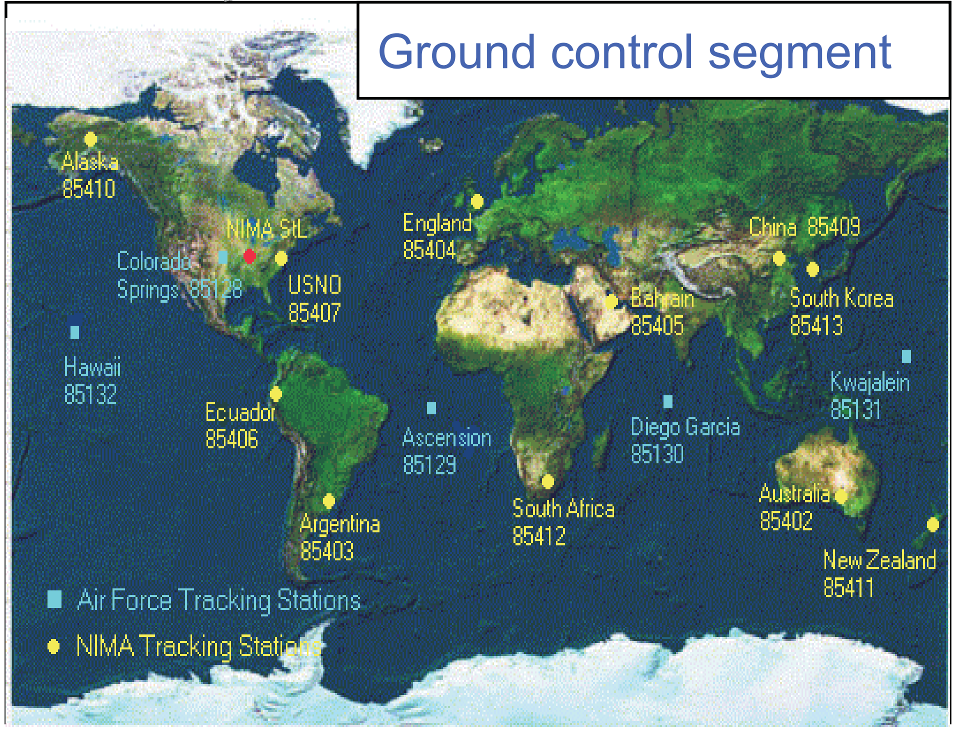
- **Services**
  - Standard Positioning Service (SPS) available to all
  - Precise Positioning Service (PPS) for "authorized" users
- **Selective Availability (SA)**
  - Purposeful degradation of the civil signal throughout 1990s, SPS horizontal positioning accuracy (95%): ~60 m
  - Discontinued by Presidential Order (2000)
  - Foresworn for GPS III by Presidential Order (2007)
- **Governance**
  - DoD (until 1996), Inter-Agency GPS Executive Board (1996-2004), U.S. National Space-Based Positioning, Navigation, and Timing Executive Committee (2004-)

GPS Segments

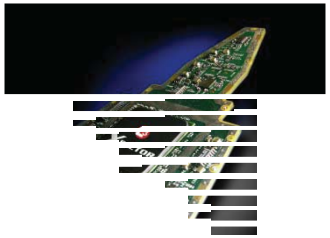
Space Segment



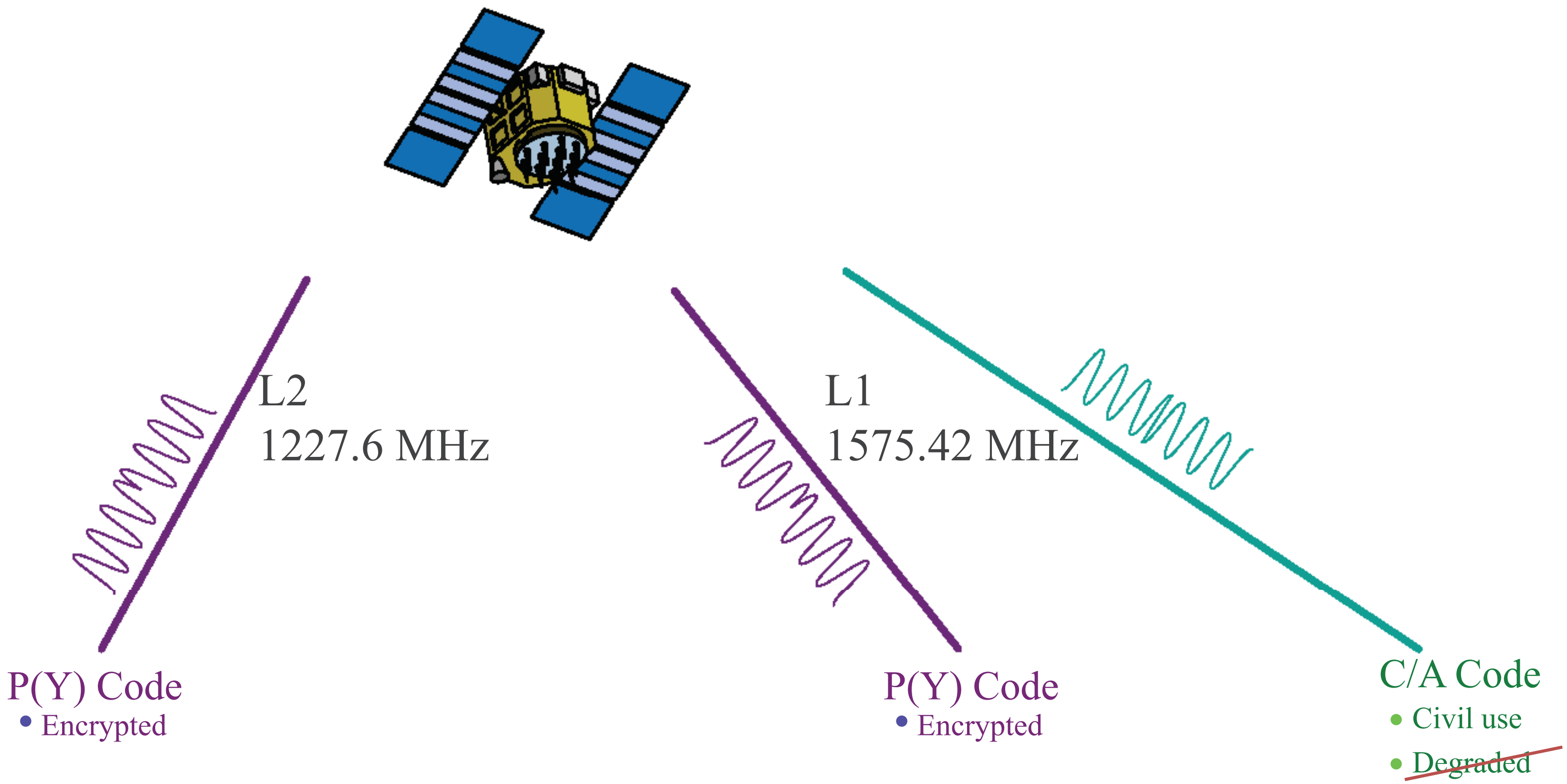
Ground control segment



User segment: civil and military



GPS Signals in mid-2005

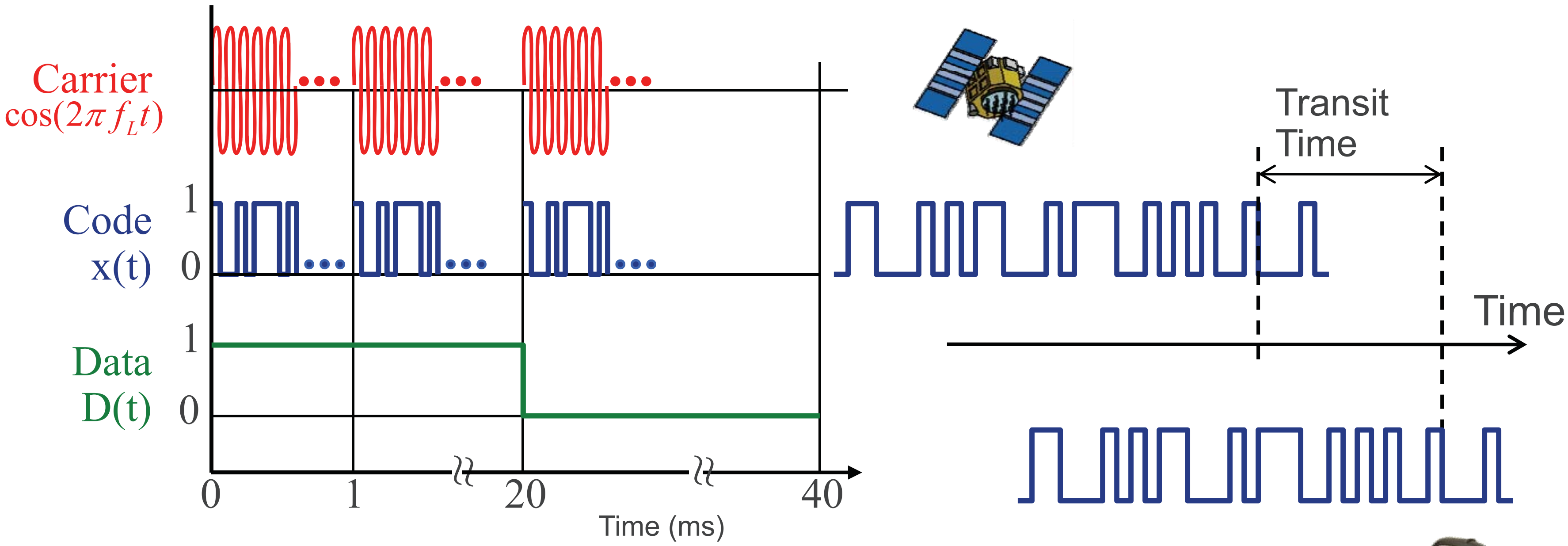


Specifications	Precise Positioning Service (PPS)	Standard Positioning Service (SPS)
Horizontal Error (95%) Vertical Error (95%)	22 m 27	< 10* ~~100~~ m < 15* ~~156~~

* Since 2 May 2000 (empirical)

Satellite Signal

GPS C/A-Code



Satellite Signal: $[D(t) \oplus x(t)] \otimes \cos(2\pi f_L t)$

$\oplus$: Mod 2 Sum

$\otimes$: Biphase Modulation

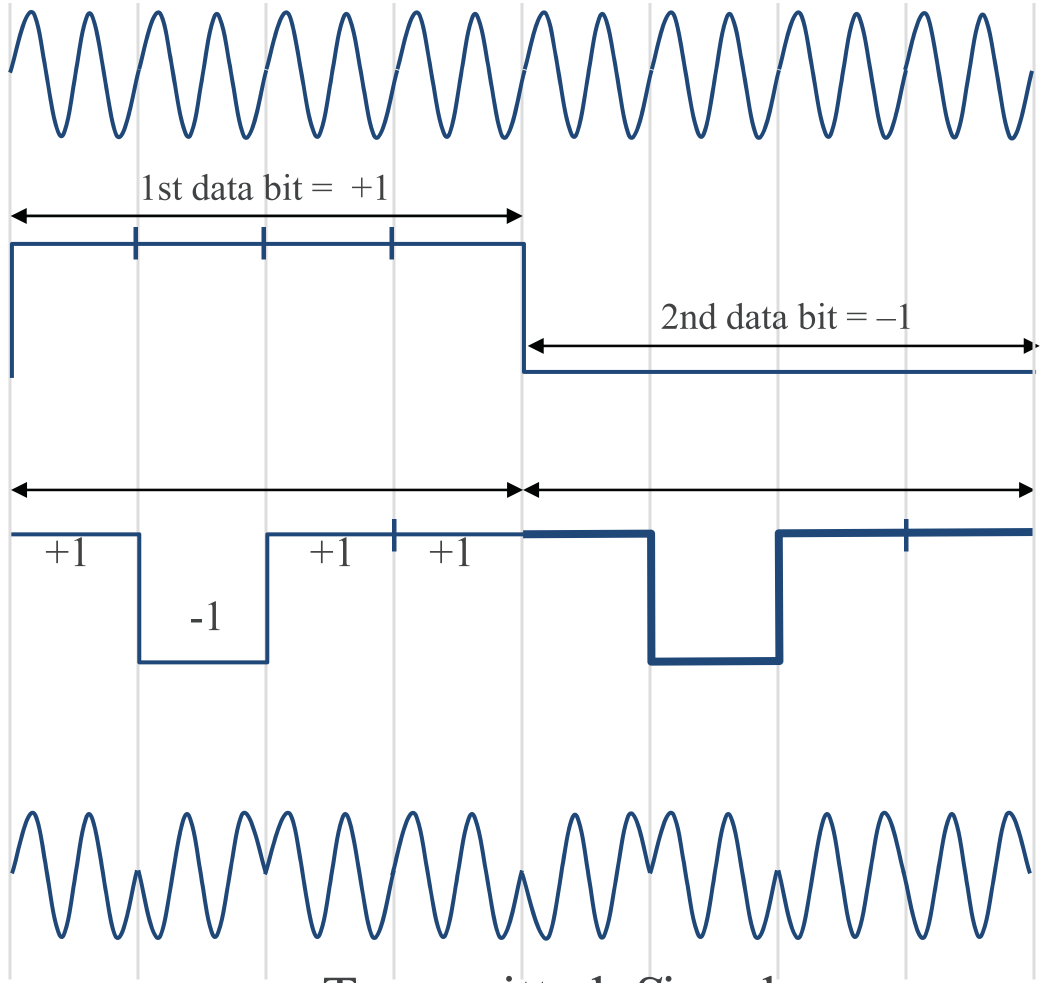
Spread Spectrum Signaling

Unmodulated Carrier

Two bits from data Stream D(t)

Two repeats of a code with 4 chips per data bit x(t)

Carrier modulated by code and data

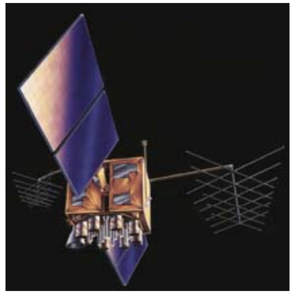


Transmitted Signal

$$s_T(t) = \sqrt{2P_T}\, D(t)\, x(t) \cos(2\pi f_L\, t)$$

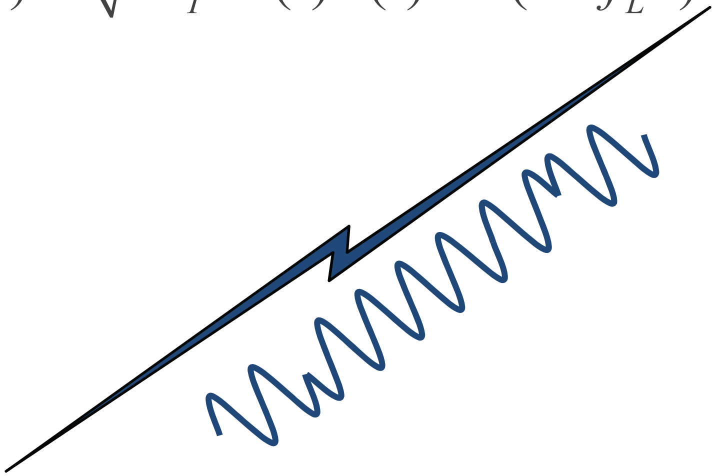
Source: Prof. Per Enge, Stanford University

A Generic GPS Signal



Transmitted Signal

$$s_T(t) = \sqrt{2P_T}\, D(t)\, x(t) \cos(2\pi f_L\, t)$$



Received Signal

$$s_R(t) = \sqrt{2P_R}\, D(t-\tau)\, x(t-\tau) \cos\left(2\pi\left(f_L + f_D\right)t + \theta\right)$$

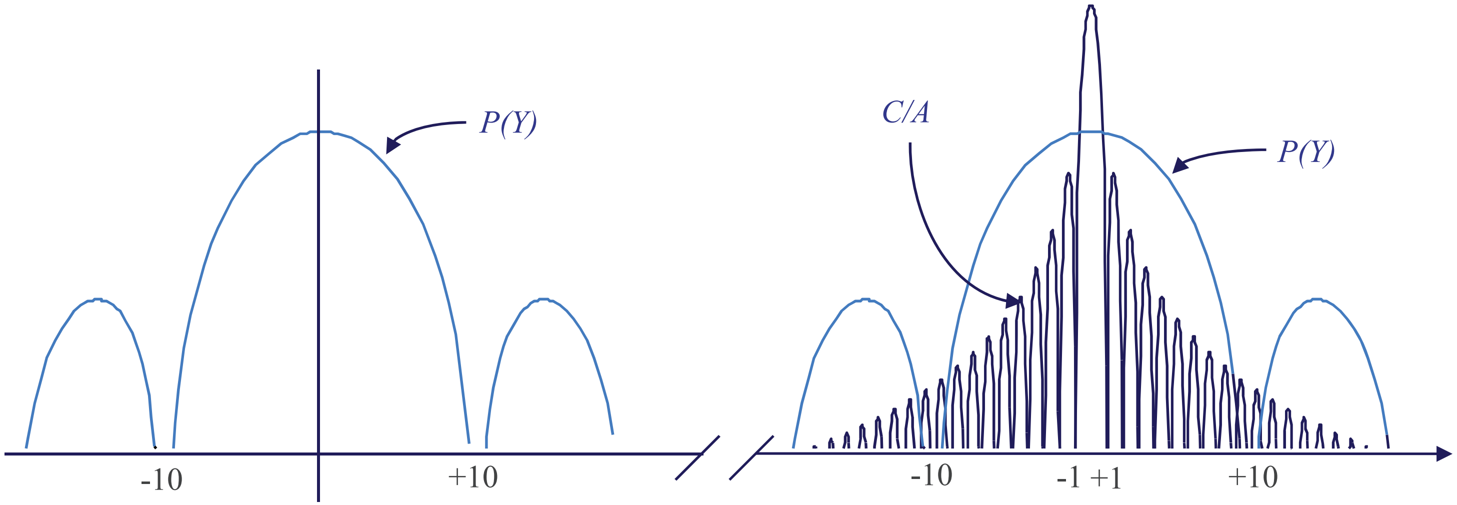
Estimate delay (τ) and Doppler (f_D)

Range $= c \cdot \tau$; Range rate $= \lambda \cdot f_D$

$D(t)$: Nav data (± 1), $x(t)$: PRN code (± 1), f_L : Carrier frequency, f_D : Doppler frequency

Amplitude Spectrum of GPS Signals

1 November 2005

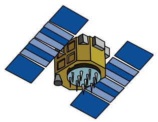


f_{L2}: 1227.6 MHz

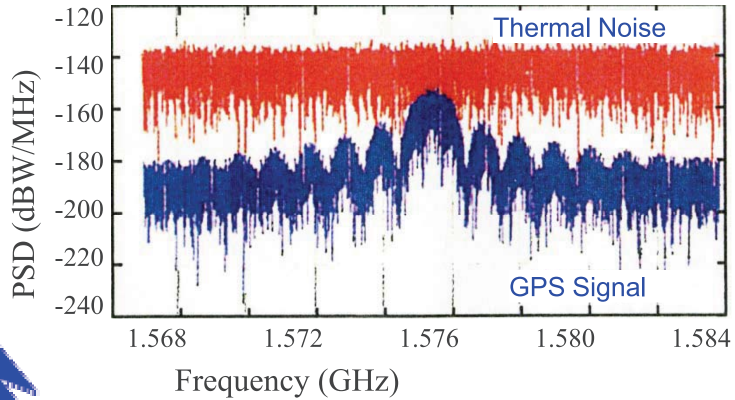
f_{L1}: 1575.42 MHz

Source: Prof. Per Enge, Stanford University

GPS Signals are Extremely Weak-1



Freq: 1563-1587 MHz (L1)
Power: ~ 27 W (C/A-Code)

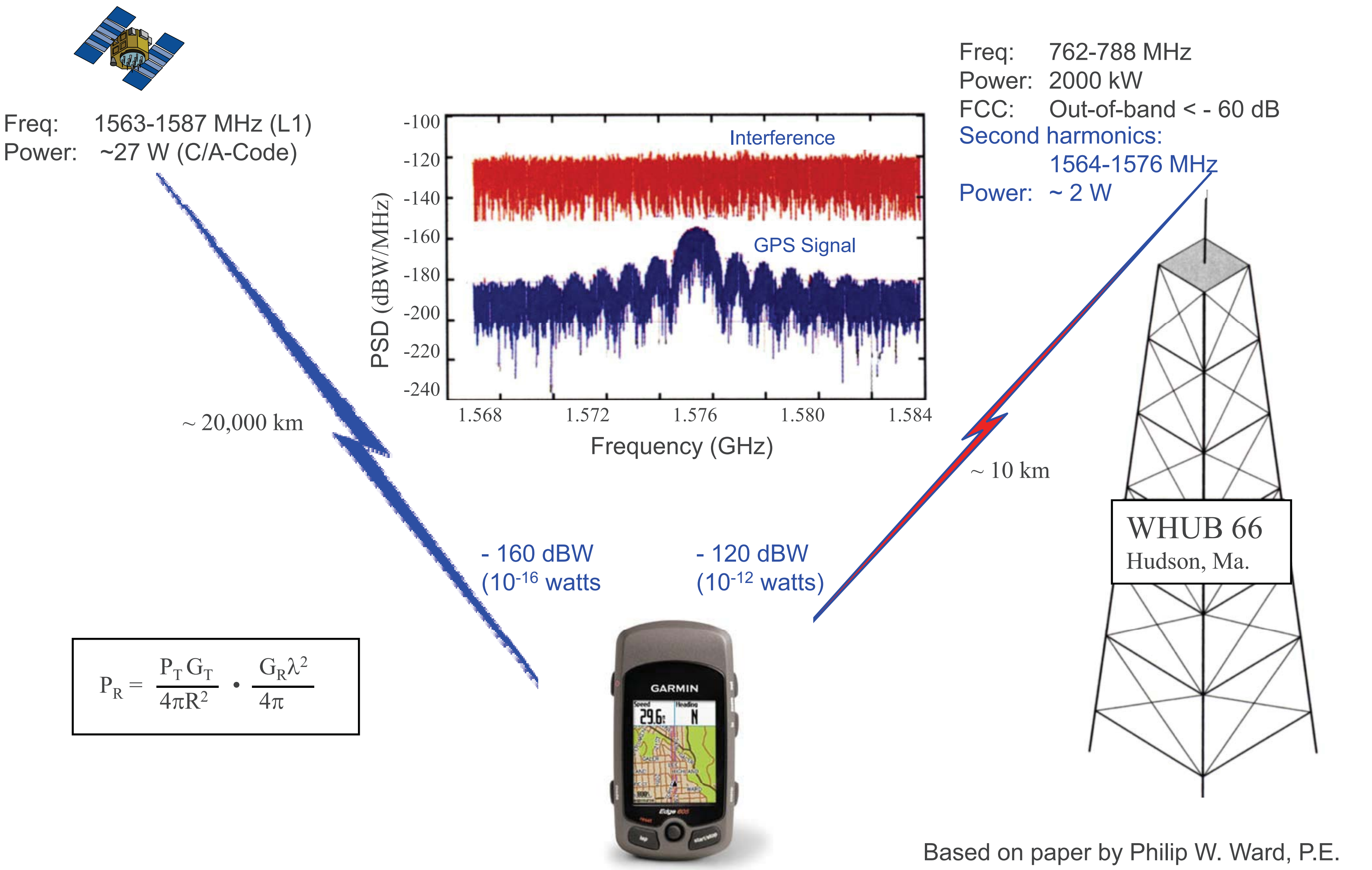


~ 20,000 km

- 160 dBW
(10^{-16} W)

$$P_R = \frac{P_T G_T}{4\pi R^2} \cdot \frac{G_R \lambda^2}{4\pi}$$

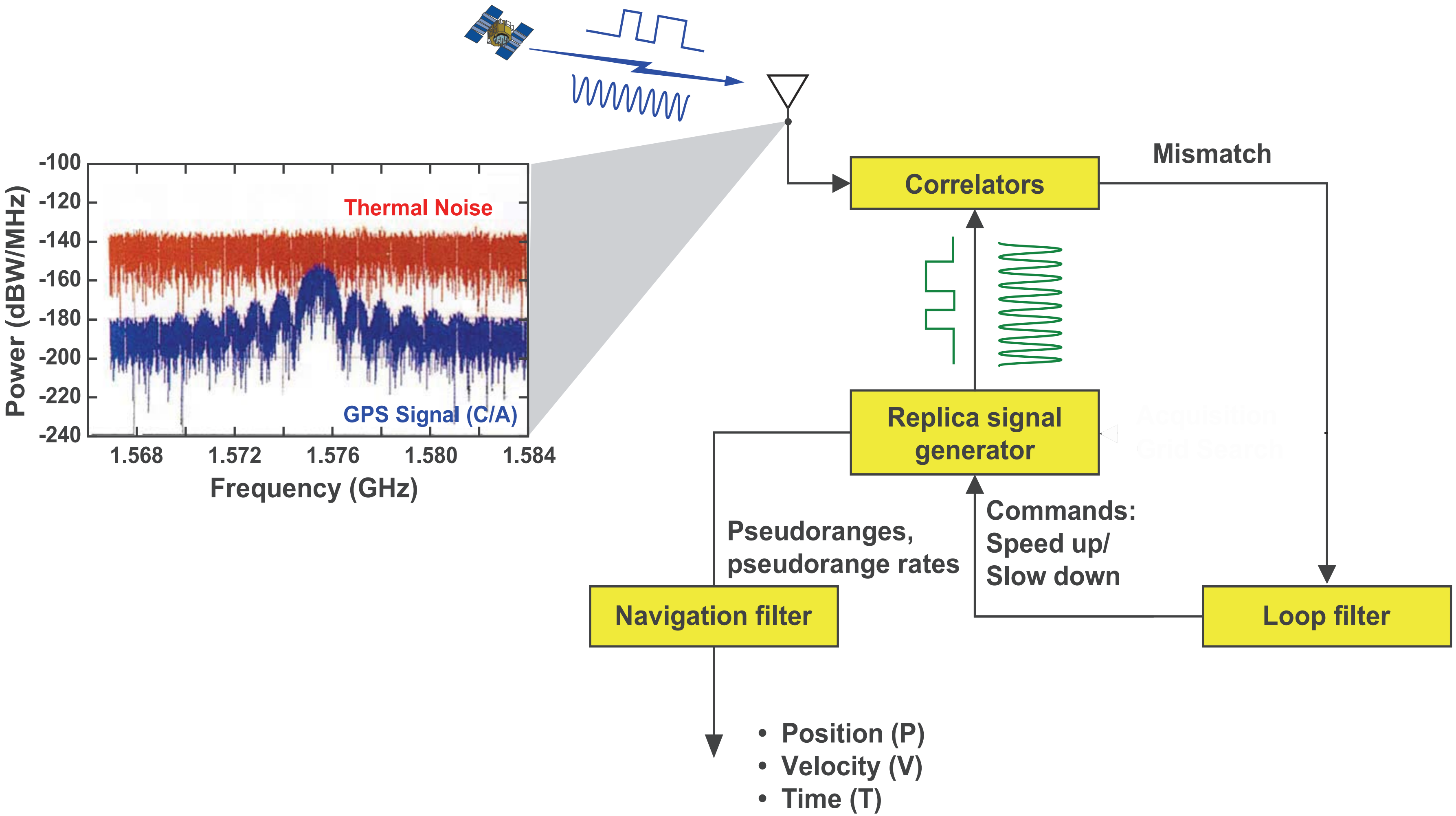
GPS Signals are Extremely Weak-2



$$P_R = \frac{P_T G_T}{4\pi R^2} \bullet \frac{G_R \lambda^2}{4\pi}$$

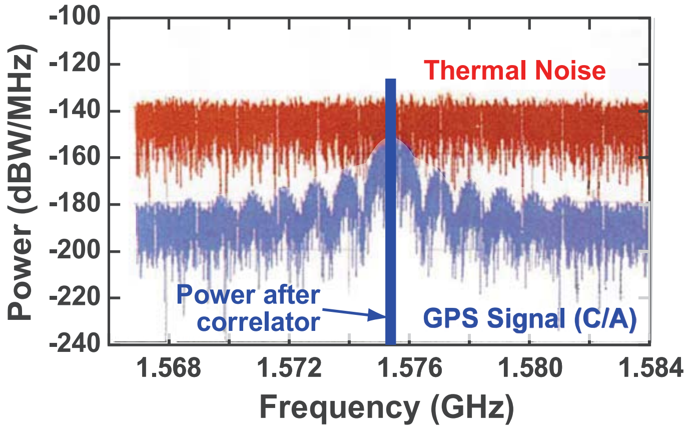
Based on paper by Philip W. Ward, P.E.

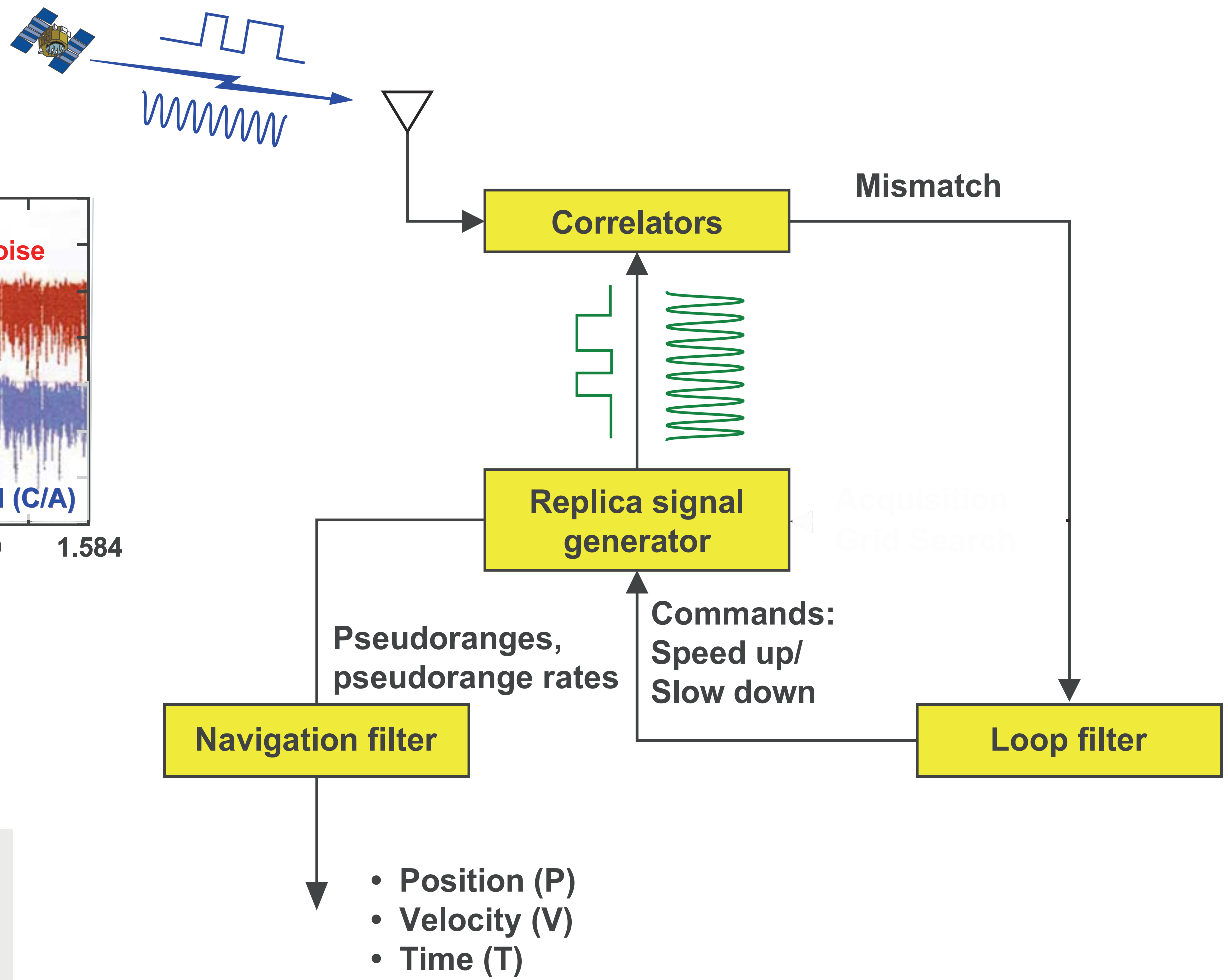
Basic GPS Receiver Architecture-1



PM082304U-p45

Basic GPS Receiver Architecture-2



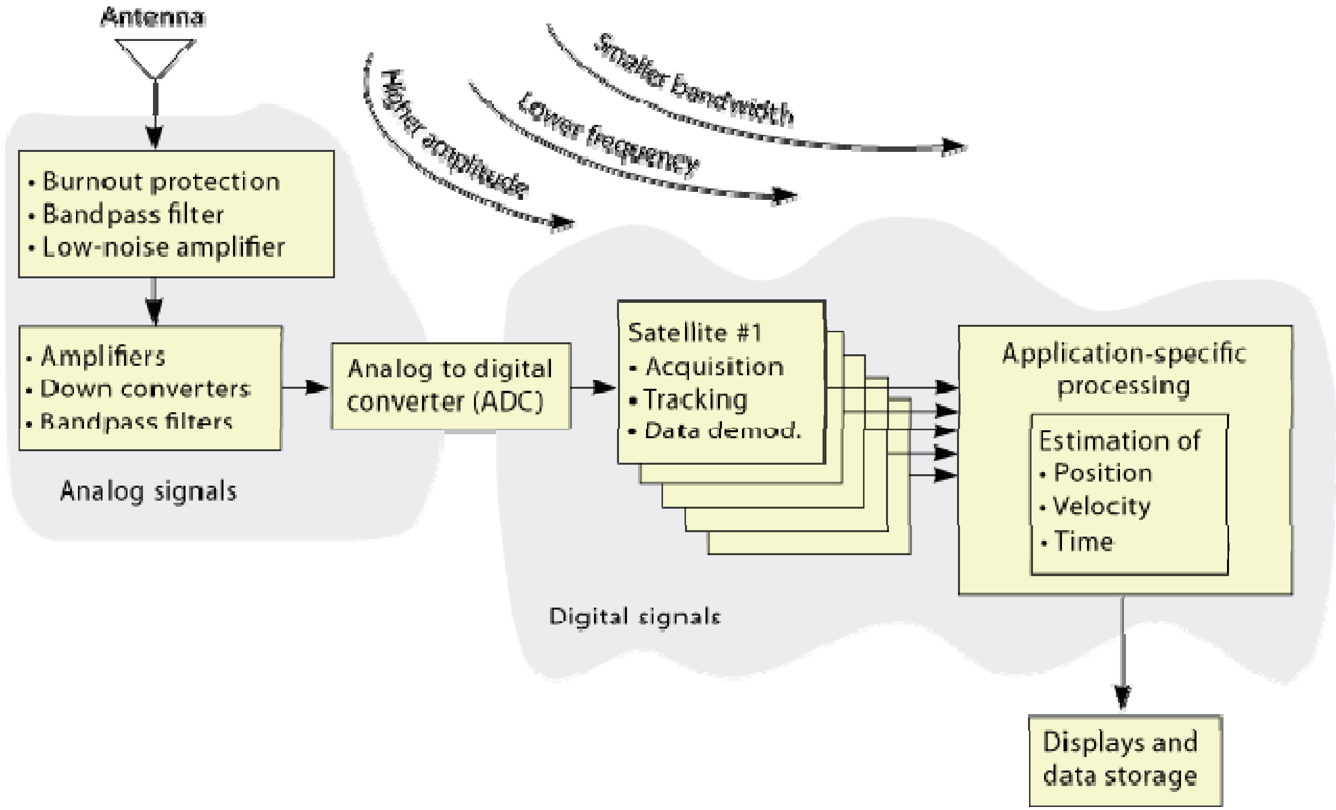


Processing Gain
$= BW_{RF} / DataRate_{BPS}$

Receiver Functions

- Condition input signal
  - Bandpass filter to suppress OOB interference
  - Down-convert
  - Digitize (A/D conversion)
- Separate signals from individual SVs
- Acquire and Track Signals
- Demodulate navigation data
- Calculate position, velocity, and time (PVT)
- Report results through user interface

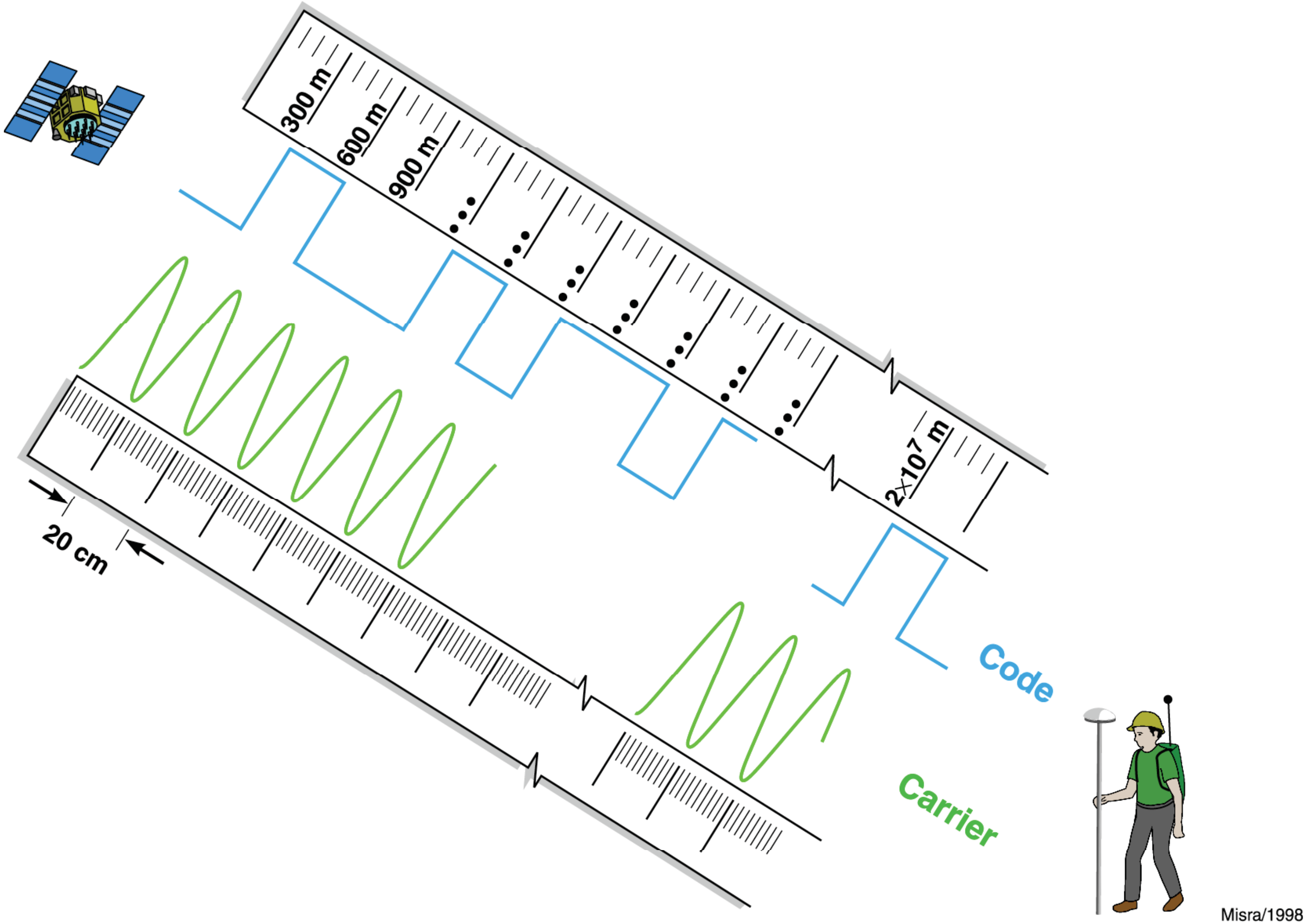
GPS Receiver Functional Diagram



Courtesy: Prof. Per Enge, Stanford University

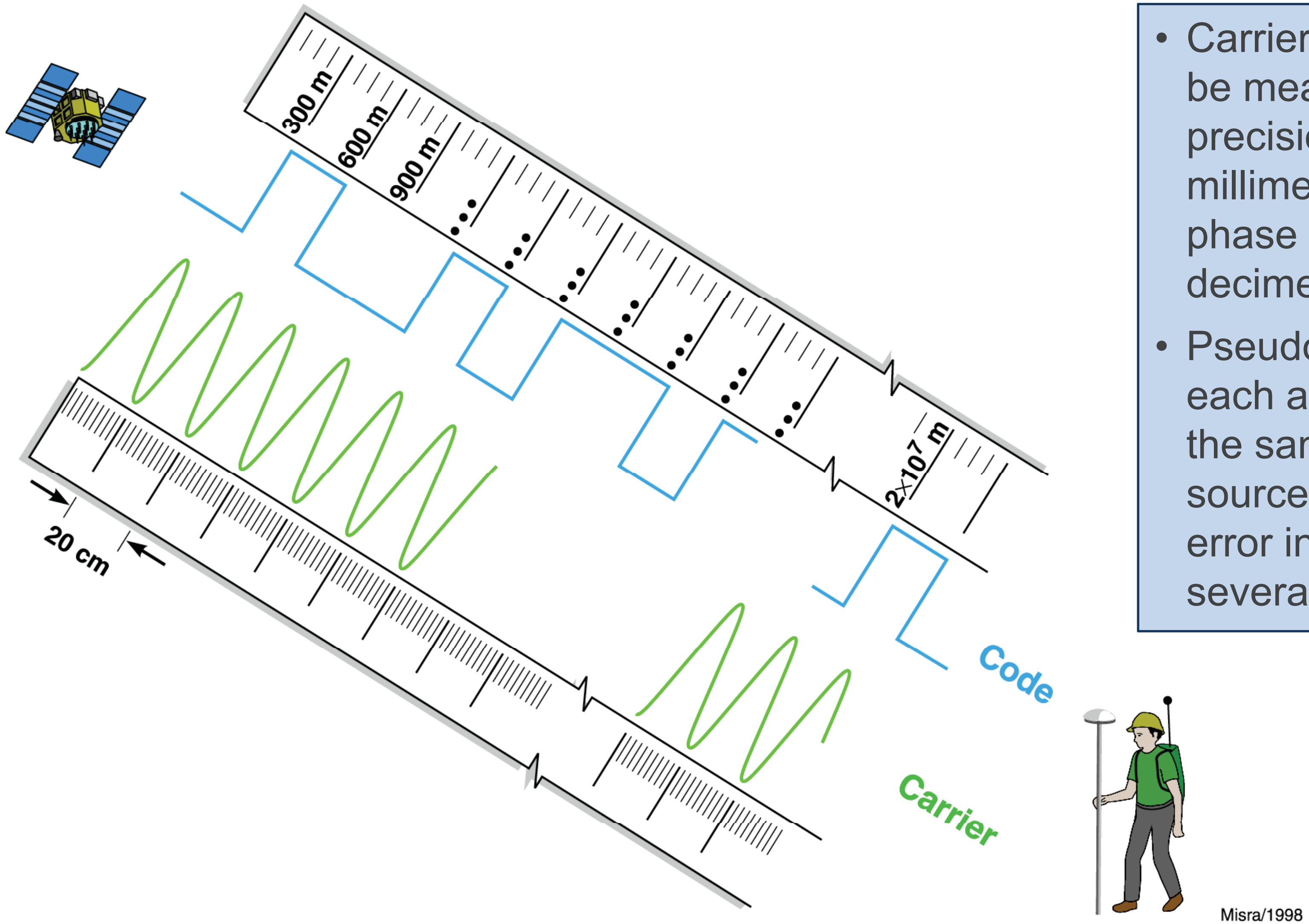
Code and Carrier Phase Measurements

A Conceptual Exercise



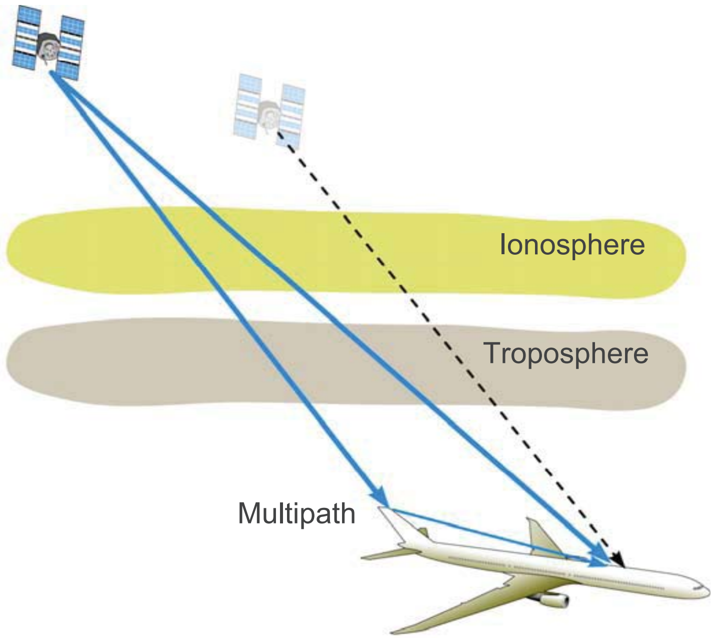
Code and Carrier Phase Measurements

Precision vs. Accuracy



- Carrier phase can be measured with a precision of millimeters, code phase with decimeters
- Pseudoranges from each are affected by the same error sources, and the error in each can be several meters

GPS Error Sources

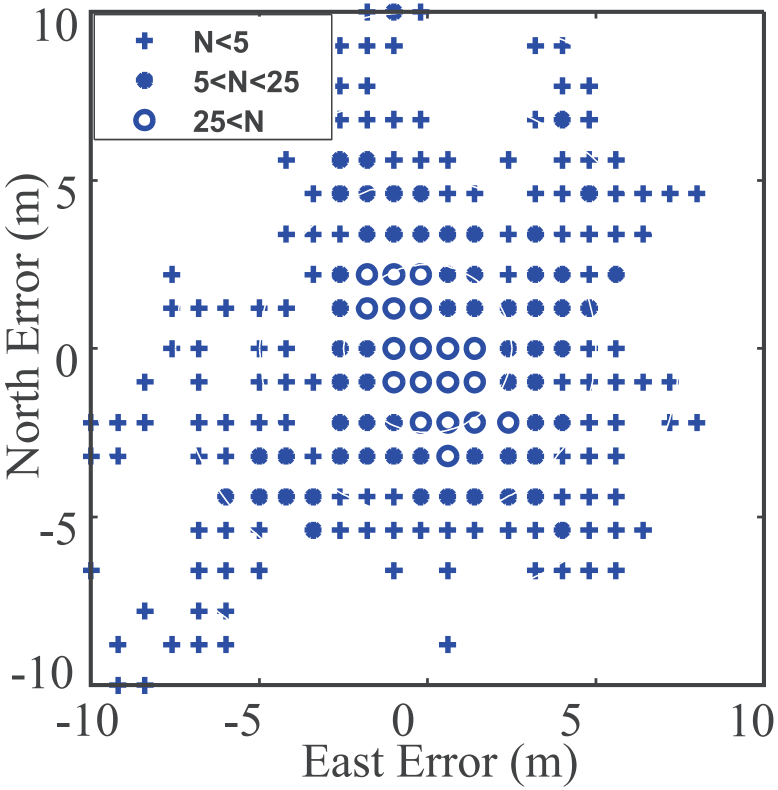


Pseudorange Error Source	Size (typical)
▪ Satellite clock/orbit error	1– 2 m
▪ Mis-modeled ionospheric delay	0– 3
▪ Mis-Modeled tropospheric delay	1
▪ Multipath	1– 3
▪ Receiver noise	< 1

Pseudorange Error: 2– 5 m

Horizontal position Error: 2– 5 m

GPS-based Position Estimates (SPS)
Sampled over 24 hours (post-SA)*



N: # points in a cell

Error: 95% (empirical)	
Horizontal position	10 m
Vertical position	15 m
Time	30 ns

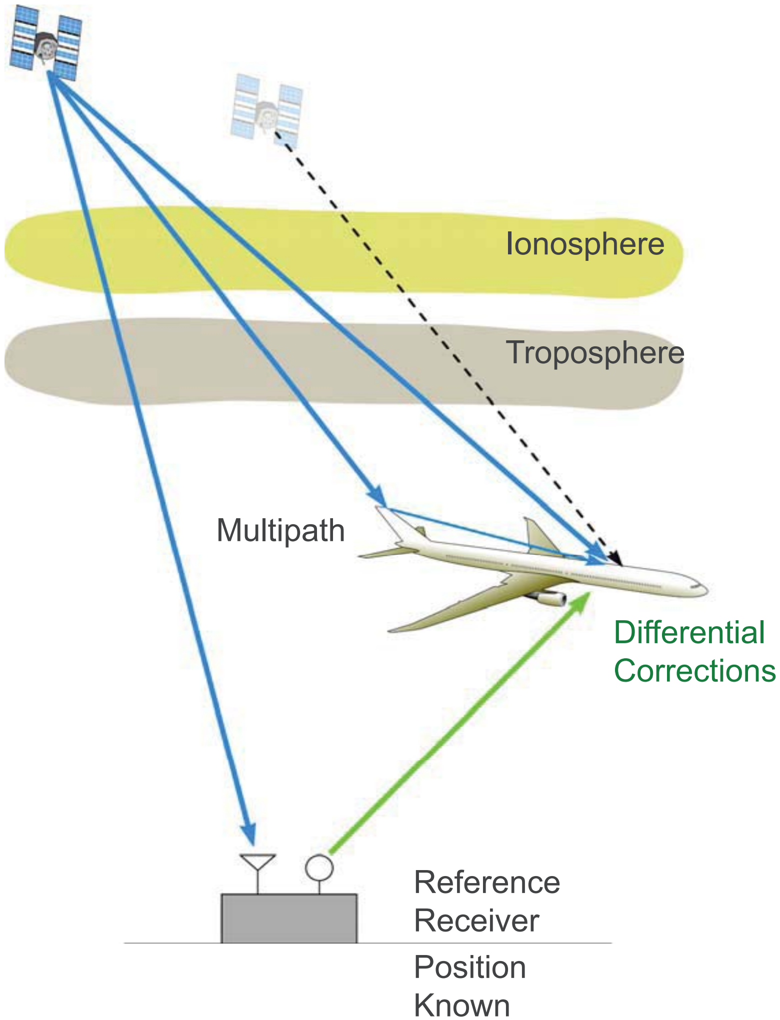
*Source: MIT Lincoln laboratory

GPS Augmentations

- **Why augment?**
  - **For better accuracy: Mitigate measurement errors**
  - **For robustness: Mitigate effects of**
    - RFI (intentional or not)
    - signal attenuation due to blockage (e.g., by foliage or building), or temporary loss of signal (e.g., going under a bridge or through a tunnel)
- **How augment?**
  - **Transmit corrections for errors that are correlated spatially and temporally**
    - Local Area Differential GPS
    - Space-Based Augmentation Systems (SBAS): WAAS, EGNOS, MSAS
  - **Assist GPS receiver with complementary technologies (e.g., inertial), signals of opportunity (e.g., eLoran), or by offloading some functions (e.g., to a cell tower in E911)**

Differential GPS (DGPS)

Mitigation of Error Sources



Pseudorange Error Source	Size (typical)	Spatially and Temporally Correlated?
Satellite clock/orbit error	1– 2 m	Yes
Mis-modeled ionospheric delay	1– 3	Yes
Mis-modeled tropospheric delay	1	Yes
Multipath	1– 3	No
Receiver noise	< 1	No

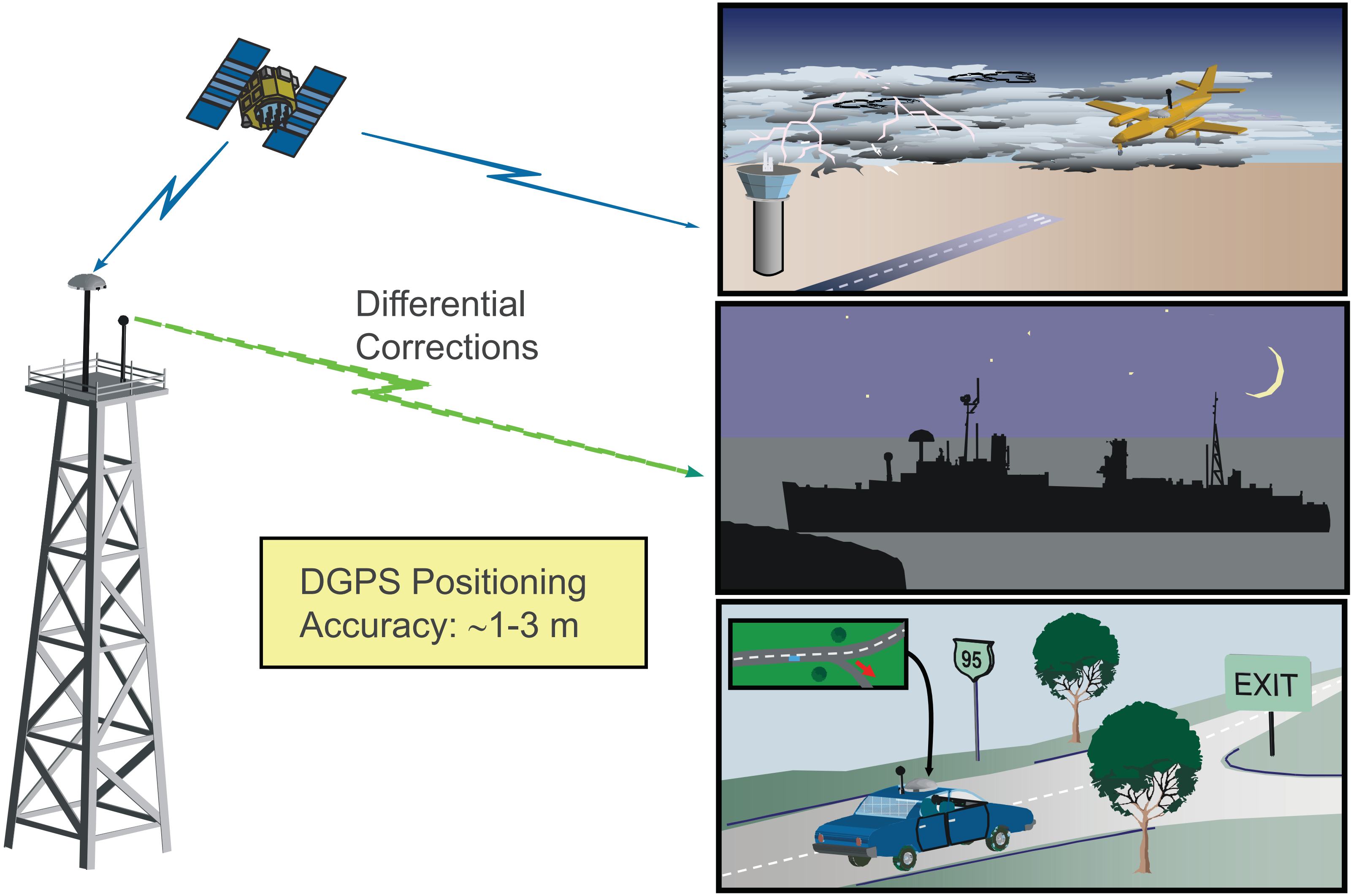
Pseudorange error: 2– 5 m
Horizontal position error: 2–5 m

Differentially Corrected
(~10 km from reference receiver)

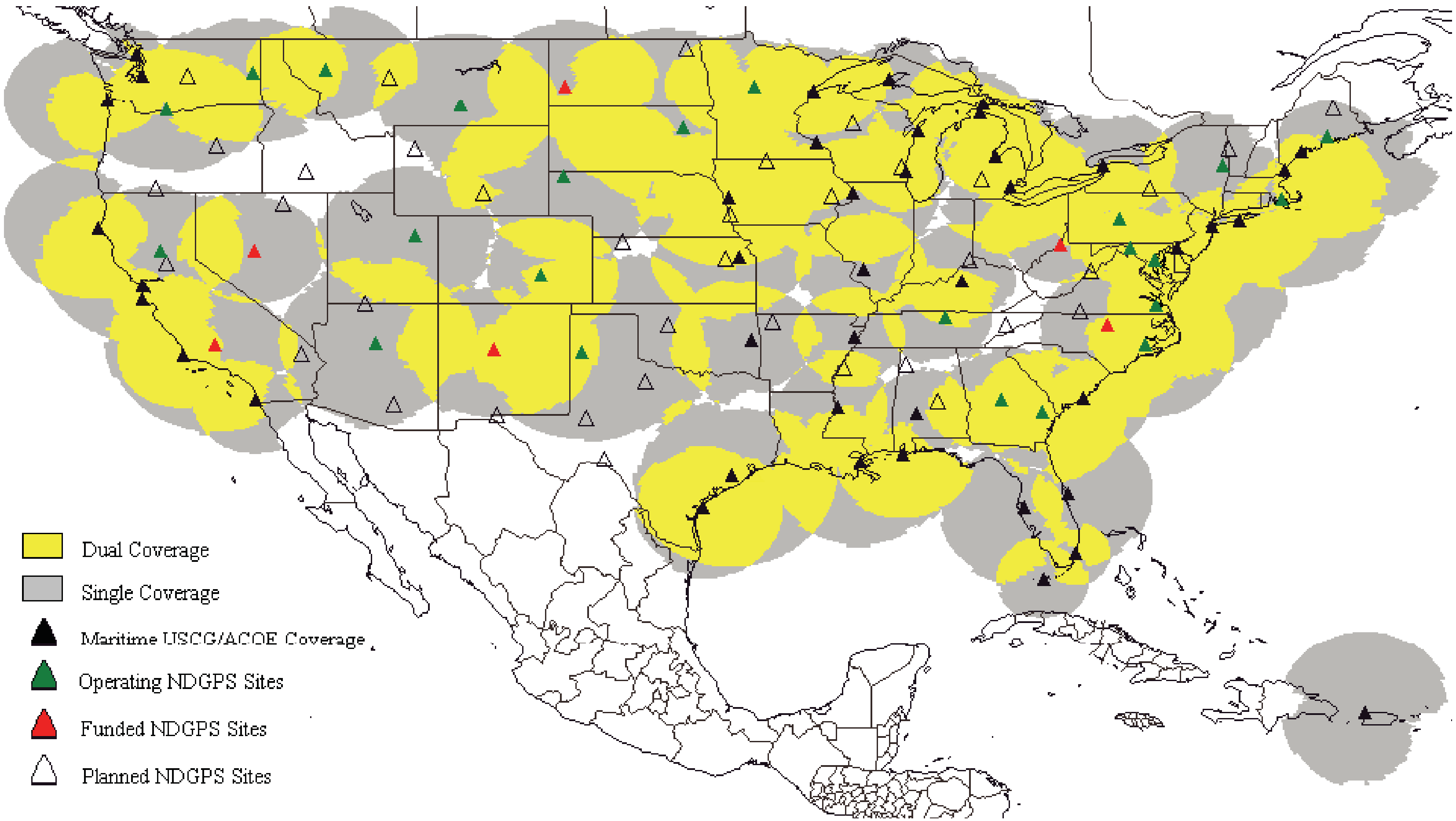
Pseudorange error: < 1 m
Horizontal position error: 1– 2 m

Local Area Differential GPS (DGPS)

Mitigation of Correlated Measurement Errors



National DGPS Coverage (2005)



In the Lower 48, single coverage: 87%, dual coverage: 55%

Satellite Navigation Overview
Outline

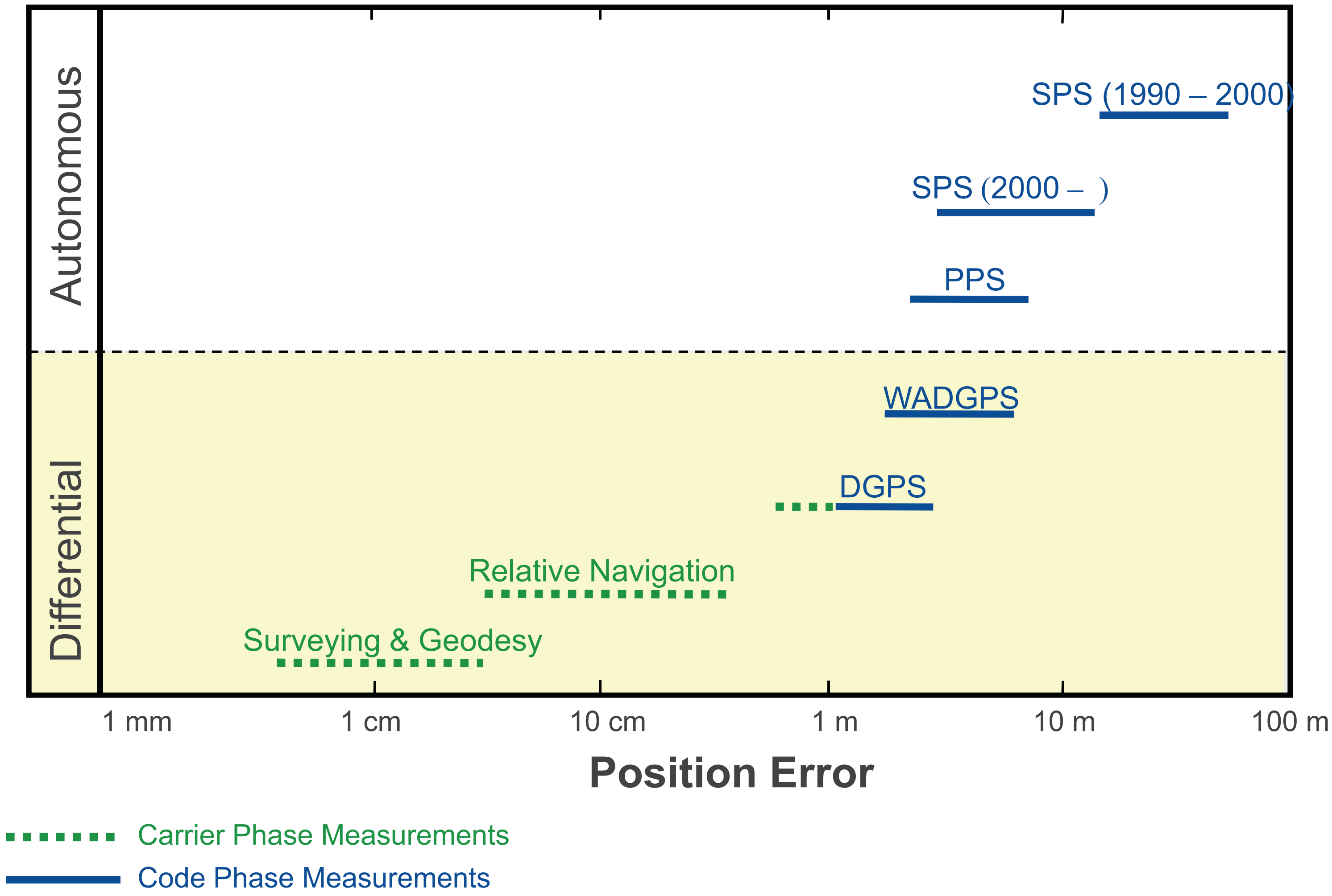
- Principles of Satellite Navigation
- GPS Overview: System, Signals and measurements, Performance
- Applications and Performance Metrics
- Potential Partners/Rivals: GLONASS, Galileo, BeiDou/Compass, …

Performance Metrics

- Accuracy
  - How good are the estimates? RMS error
- Error Bounds
  - Your error is no worse than x (with probability 0.999…9)
- Integrity of Signals
  - The signals on which your estimates are based are genuine. (Probability)
- Availability of Service
  - Consistent with your requirements. (Probability)
- Continuity of Service
  - For the next x seconds, consistent with your requirements. (Probability)

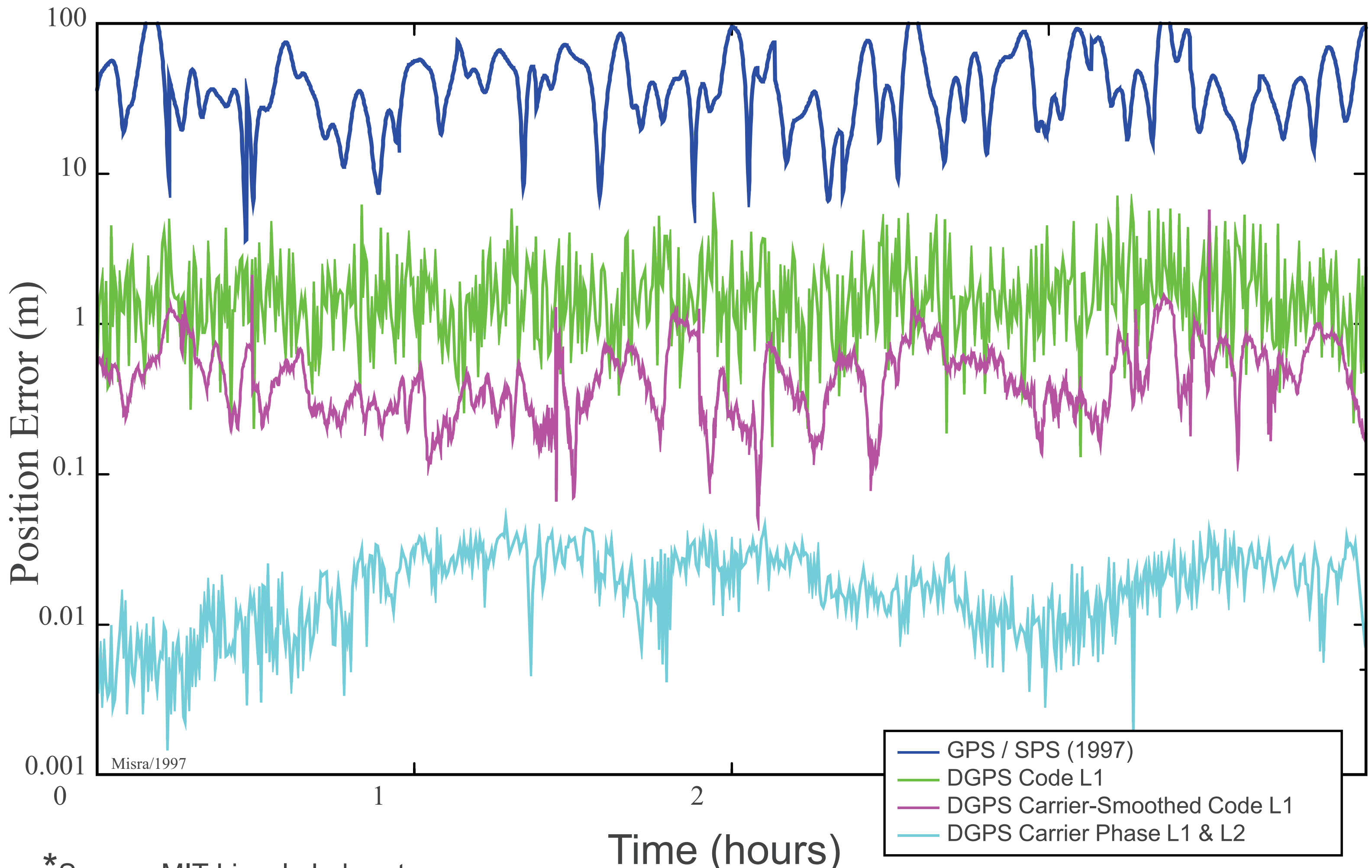
Positioning Accuracy Hierarchy

GPS and Its Augmentations



PM112905U-p3

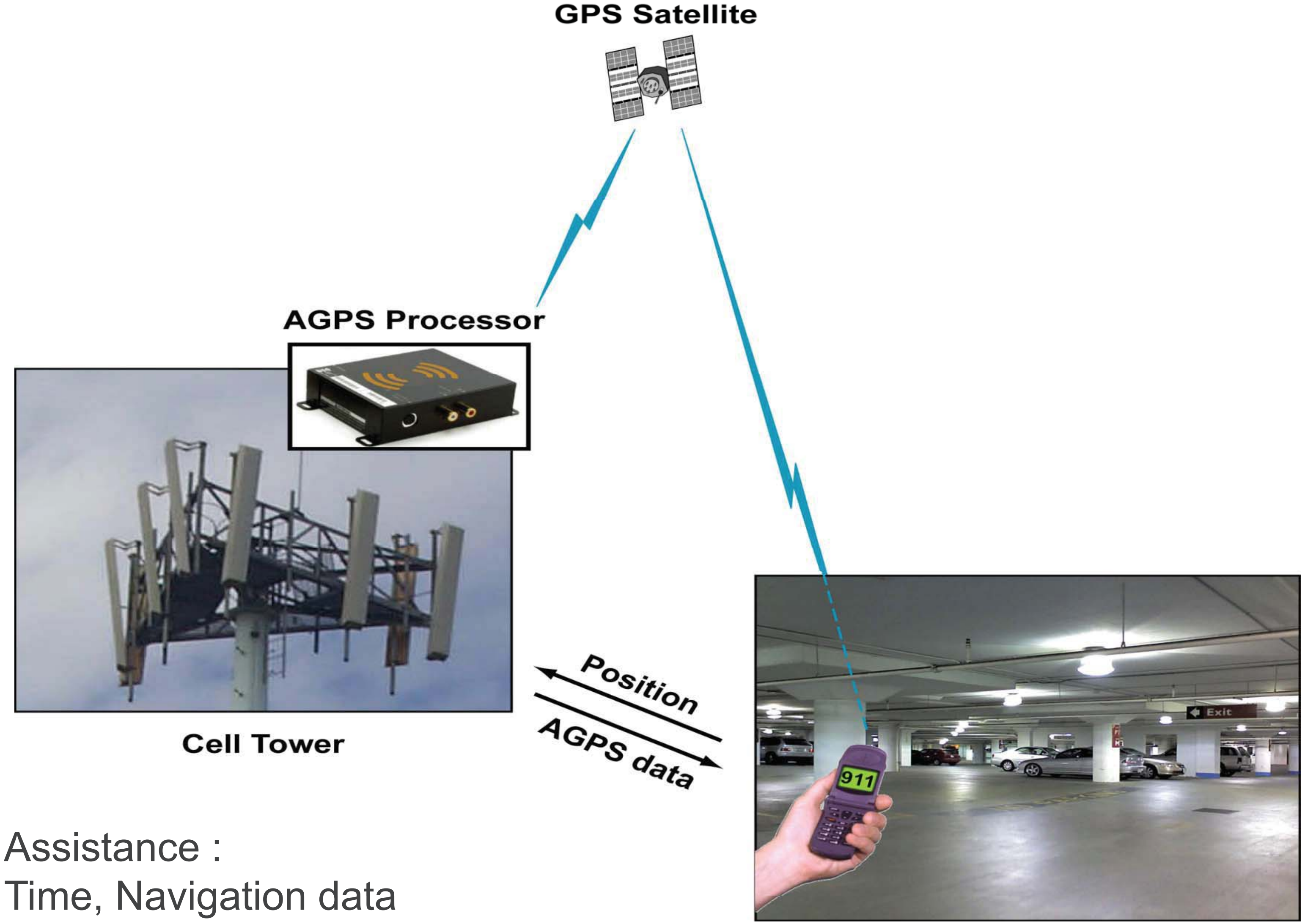
Real-Time Position Estimates from GPS (1997)*



*Source: MIT Lincoln Laboratory

GPS Applications

Assisted GPS (AGPS)



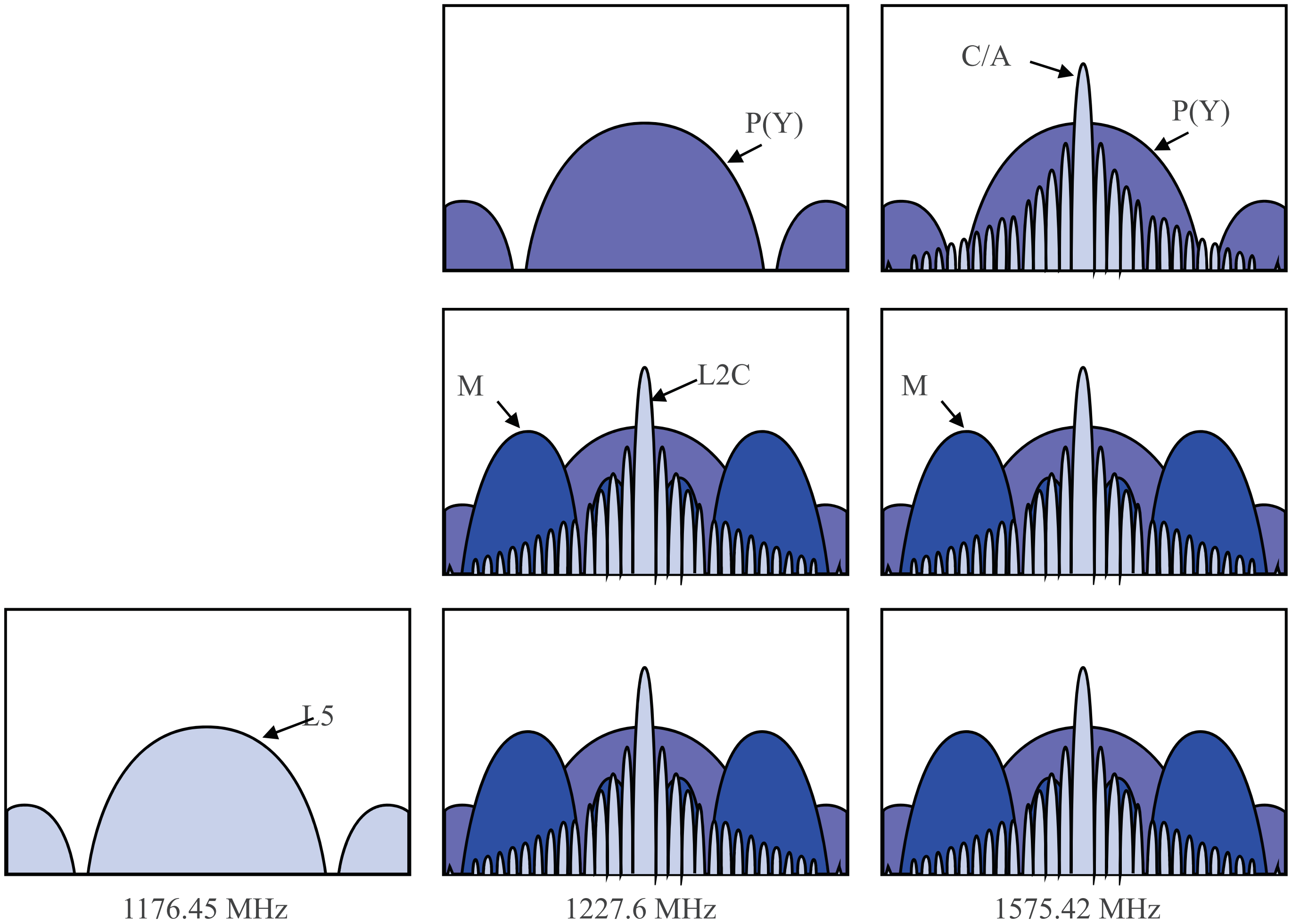
Assistance :
Time, Navigation data

Satellite Navigation Overview

Outline

- Principles of Satellite Navigation
- GPS Overview: System, Signals and measurements, Performance
- Applications and Performance Metrics
- **Potential Partners/Rivals: GLONASS, Galileo, BeiDou/Compass, …**

Evolution of GPS Signals



Block II / IIA / IIR

1989 - 2005

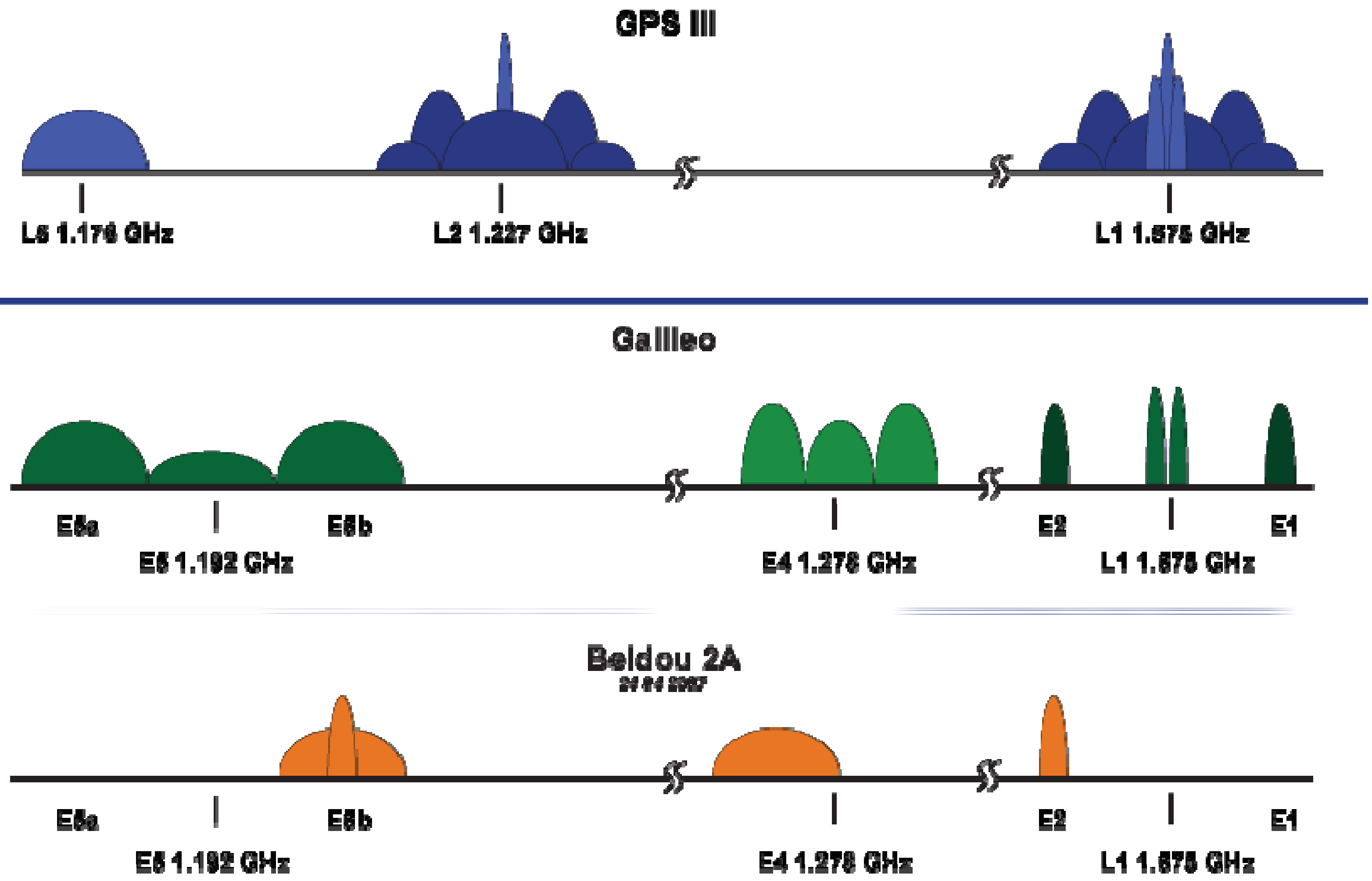
Block IIR-M

Starting in 2005

Block IIF

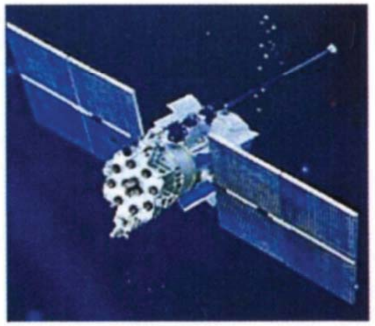
Starting in 2009

Frequency Plans*



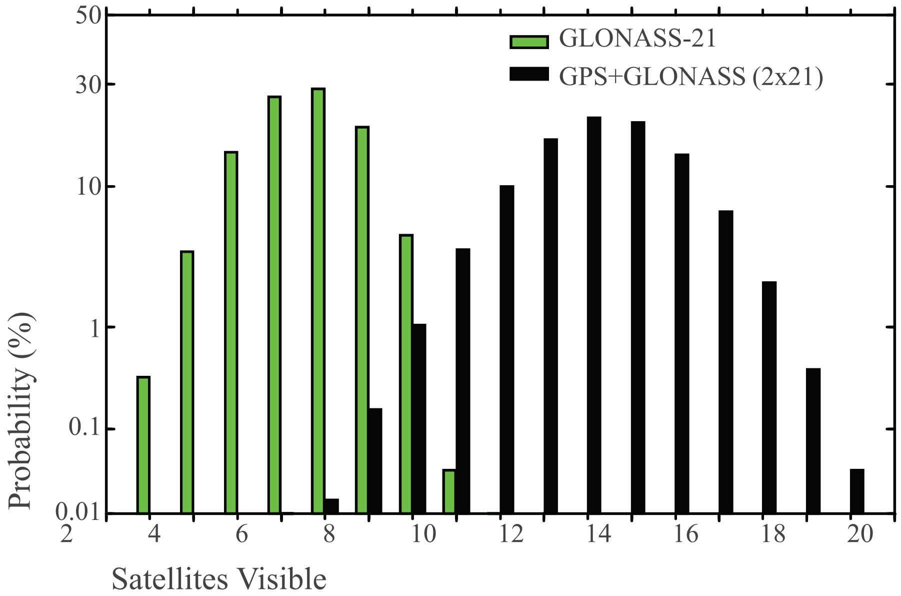
*Adapted from T. Grelier et al., Inside GNSS, May/June 2007

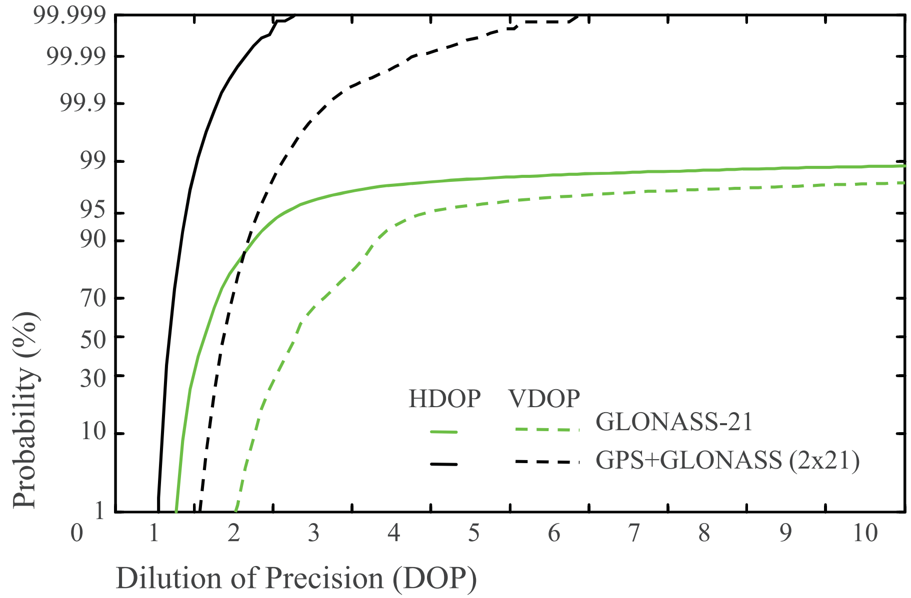
GLONASS



- History
  - Developed by Soviet Union, first launch: 1982
  - Declined under Russia, but newly revived
  - Similar to GPS: Passive, one-way ranging
  - 10-12 working satellites over the past 5 of years, currently 16
  - No significant user base
- Constellation
  - 24 satellites in 3 orbital planes, 64.8º inclination
  - 19,100 km altitude, 11 ¼ hour period
- Signals
  - 3 allocated bands: G1 (1602 MHz), G2: (1245 MHz), G3 (?)
  - C/A-like code: 511 chips, 1 ms code period, 50 bps data
  - All SVs use same PRN with frequency division multiple access (FDMA) using 16 frequency channels, reused for antipodal SVs
- Plans: 18 SVs in 2008, full constellation in 2011 (?)

GPS+GLONASS Satellite Visibility

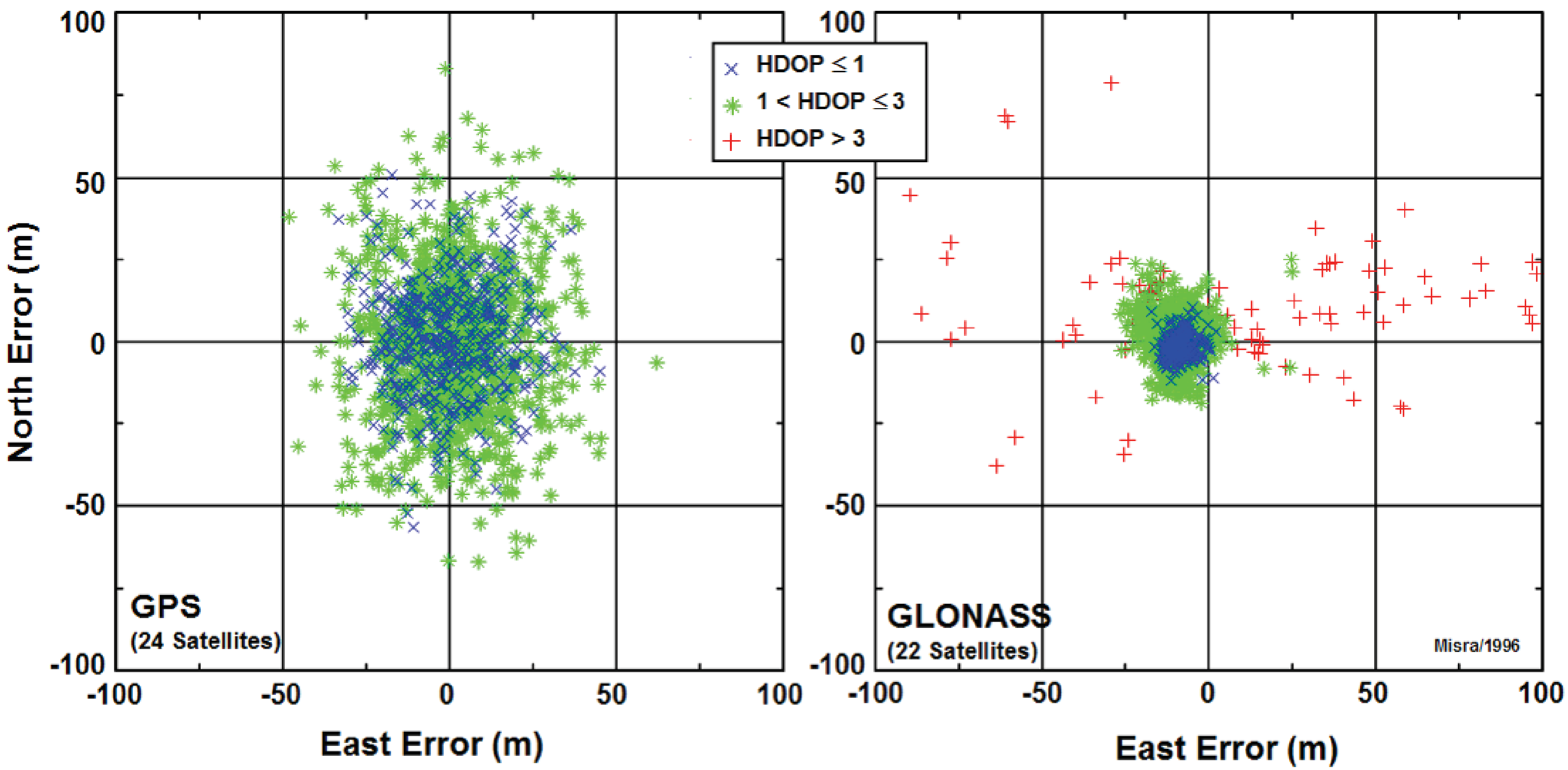




Misra/1997

GPS & GLONASS Position Estimates*

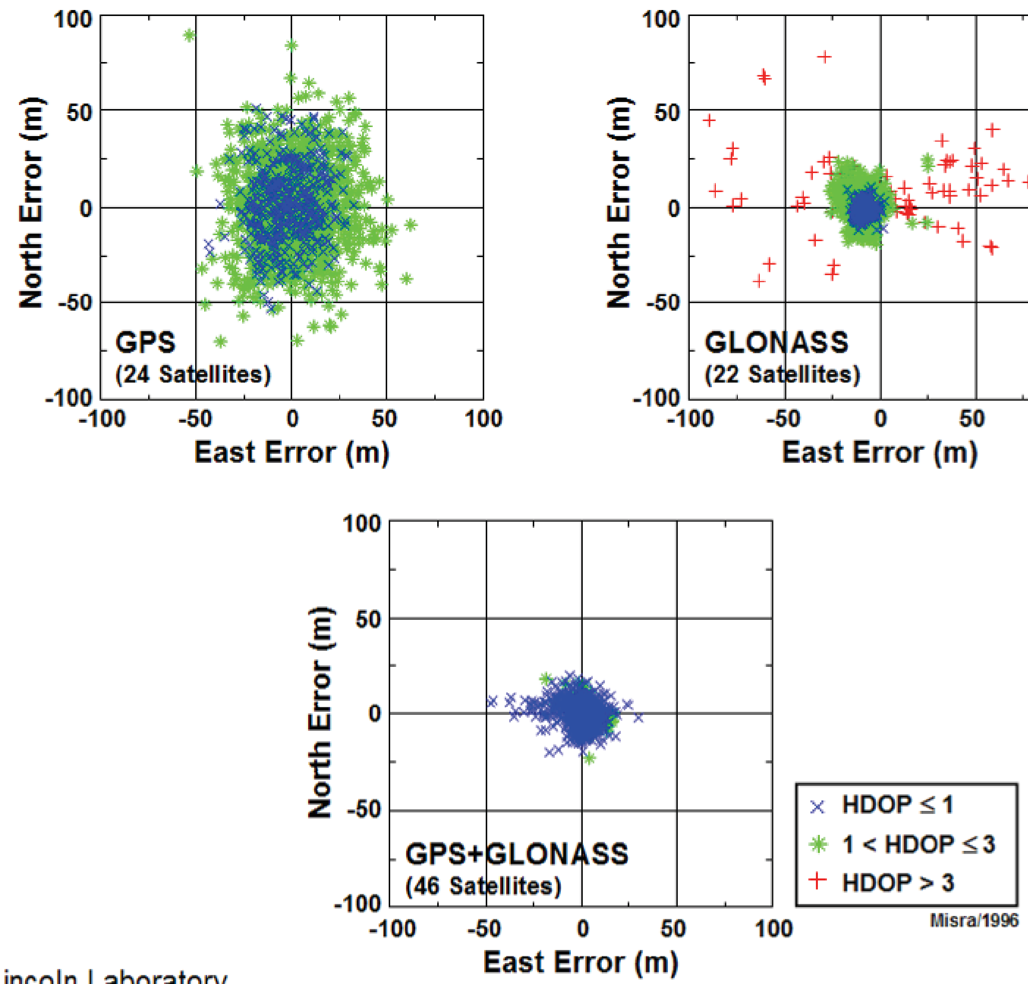
1-Minute Samples, 15 June 1996



*Source: MIT Lincoln Laboratory

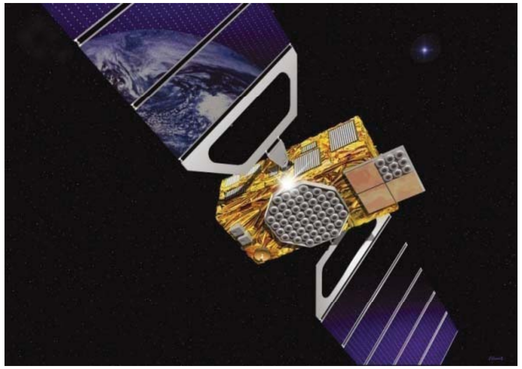
GPS & GLONASS Position Estimates*

1-Minute Samples, 15 June 1996



* Source: MIT Lincoln Laboratory

Galileo



- **European-owned: planned public-private partnership didn't work out**
- **"Seen" as a civil system, but military role may emerge**
- **5 services**
  - **Free:** Open Service
  - **For a Fee:**
    - Commercial Service
    - Safety-of-Life Service
    - Public Regulated Service
    - Search & Rescue Service
- **30 MEOs in 3 planes inclined at 56°**
- **First experimental satellite launched in 2005**
- **Appears to have recovered from recent setbacks; system operational around 2013**

PROGRAM OBJECTIVES

- Objectives of Galileo:
  - Increased overall performance
  - Civil system in contrast to GPS
  - Independent **and** interoperable with GPS
  - Better robustness
  - Certified quality of services
  - Qualified for safety critical applications
  - …

24 June 2005 1 Institute of Geodesy and Navigation

BeiDou/Compass

- Chinese
- BeiDou: Regional System
  - Active system
  - 2 - 3 geostationary satellites orbited in 2000 – 2003
- Compass: GNSS
  - 1 MEO launched in 2007
-

Summary: Take-Away Points

- Satellite navigation systems exploit basic properties of radio waves: Transit exploited the Doppler effect, GPS exploits the known speed of propagation
- GPS is based on the old idea of trilateration, but implemented with the technology of the second-half of the 20^{th} century: space-based radio transmitters, ultra-stable clocks, and spread spectrum signals
- A GPS receiver measures pseudoranges to the satellites by measuring pseudo-transit times of radio signals. It takes 4 satellites (i.e., 4 pseudoranges) in order to estimate position (x, y, z) and time t
- With a clear view of the sky, it's easy to get positioning accuracy of several meters with a \$100 GPS receiver, or relative positioning accuracy of millimeters with a pair of \$1000 receivers.
- GPS satellites are 20-watt transmitters 20,000 km away, so the signals reaching the earth are very weak and, therefore susceptible to interference.
- The success and breadth of GPS applications is attributable largely to "the chip." The VLSI revolution was well-timed for GPS