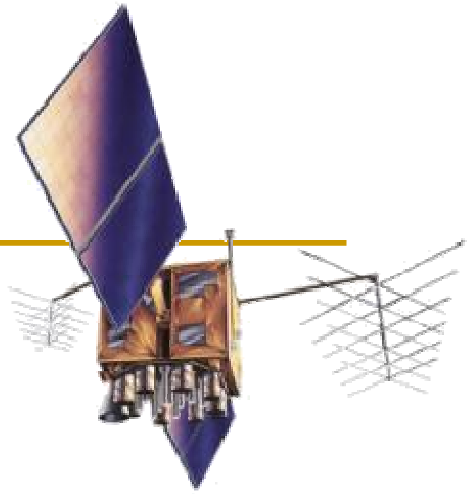
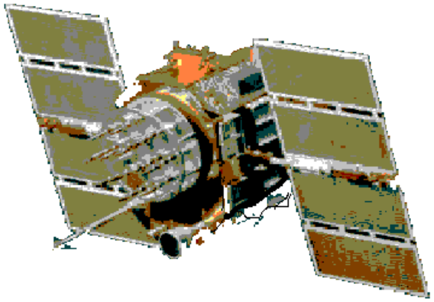


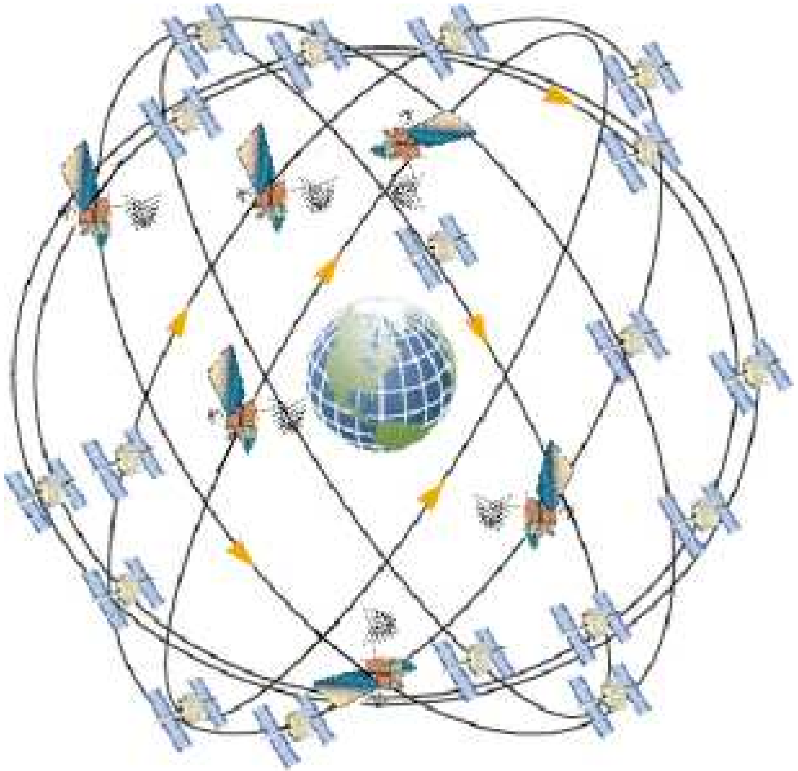
Introduction to GPS and other Global Navigation Satellite Systems

Michael C. Moreau, Ph.D.
Navigation and Mission Design Branch
NASA Goddard Space Flight Center



36th Annual Time and Frequency Metrology Seminar
9 June 2011

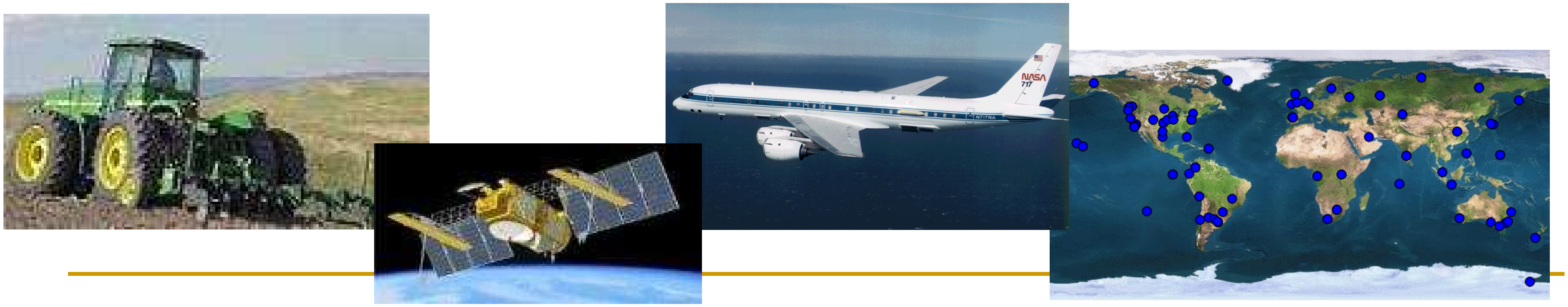
Outline



- Introduction
- Satellite Navigation System Fundamentals:
  - Satellites & Signals
  - Solutions
  - Errors
- The U.S. Global Positioning System
  - History, Status, and Future
- Other Global Navigation Satellite Systems and Augmentations:
  - GLONASS, GALILEO, BEIDOU (COMPASS), QZSS

Applications of Satellite Navigation are Everywhere…

- Satellite navigation technology is embedded in a wide range of mobile consumer devices to enable navigation and location-based services
- Applications touch many aspects of our every-day lives



Satellite Navigation and Precise Timing are Fundamentally Linked

- Precise timing is fundamental to realizing performance from satellite navigation systems
- Satellite navigation systems allow users to synchronize clocks and calibrate and control oscillators in any location with access to an antenna
- Applications range from use in tele-communications networks to timing laboratories
- GPS has become a primary system for distributing time and frequency globally

Importance of Precise Timing to GPS

- A typical GPS receiver provides user position estimates accurate to a few meters by measuring the range (signal delay) between the user and multiple GPS satellites
- Assume the specified ranging error contribution from the satellite clock is one meter:
  - ❑ One-meter ranging error is equivalent to 3.3 ns
    (one meter / speed of light = 3.3×10^{-9} s)
- GPS satellite clock error must be maintained below this level over a 12 hour period (typical duration between updates to the timing data broadcast by the satellite)
  - ❑ Requires a clock with about one part in 10^{13} stability;
    3.3×10^{-9} s / 43200 s = 0.8×10^{-13}

Atomic Clocks in Space

- GPS satellites carry redundant rubidium or cesium oscillators (or a combination)
  - Precise frequency standard provides a reference for generating the ranging signals transmitted by the satellites
- Clocks on the satellites are steered by GPS ground controllers to Coordinated Universal Time (UTC) as maintained by the US Naval Observatory (USNO)
  - A direct reference to UTC(USNO) can be made automatically by most timing receivers by using corrections included in the broadcast GPS NAV message.
- By mutual agreement, UTC(USNO) and UTC(NIST) are maintained within 100ns (and frequency offset $<1\times10^{-13}$)
- GPS enables precise time and frequency transfer on a global scale.

Relativistic Effects in GPS

- Atomic clocks in GPS satellites are given a fixed fractional frequency offset of $-4.46475\text{x}10^{-10}$ to compensate for relativistic effects in the GPS satellite orbits
  - Second-order Doppler shift – a clock moving in an inertial frame runs slower than a clock at rest
  - Gravitational frequency shift – a clock at rest in a lower gravitational potential runs slower than a clock at rest in a higher gravitational potential
- Without this offset, GPS satellite clocks would gain ~38 microseconds per day relative to clocks on the ground (~11 km range error)
- GPS receivers apply an additional correction of up to 23 ns (~7 meters) to account for eccentricity in the satellites' orbit

Satellite Navigation System Fundamentals

Satellite Navigation Fundamentals

- Satellite navigation is based on:
    - The precise measurement of time
    - The constancy of the speed of light
- GPS and other systems use the concept of trilateration:
    - Satellite (transmitter) positions are known
    - Receiver position is unknown
- Receiver position is estimated using measurements of the transit-time of a signal between the satellite and receiver

Measurement Equation

- GPS receiver measures range or distance to the GPS satellite by measuring the transit time of the signal:

$$\rho_k = c\left(\underset{\uparrow}{t_r} - \underset{\uparrow}{t_T}\right)$$

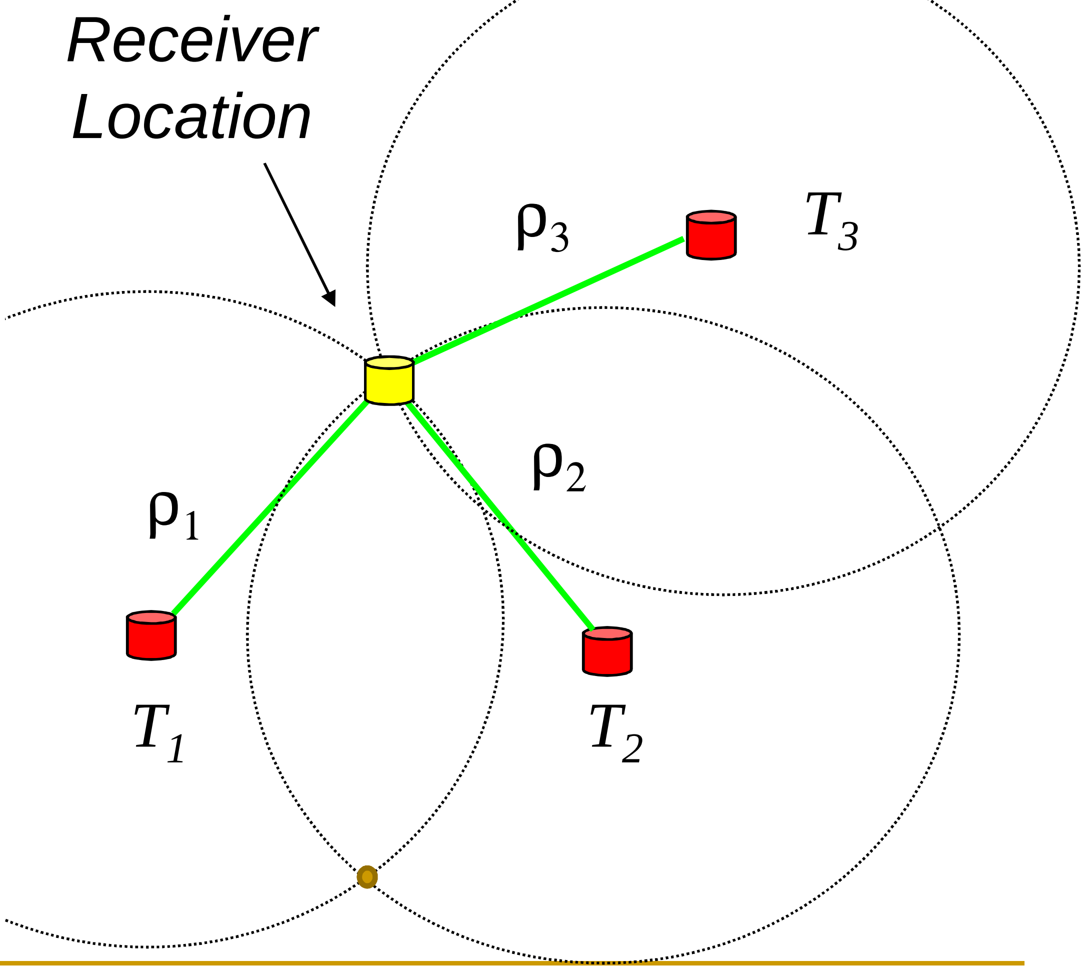
time of signal reception, (based on receiver clock, can be significantly in error)

time of transmission, encoded in signal by GPS satellite clock (known precisely)

- Measurement is called “pseudorange” because the measurement includes the transit time biased by the error in the receiver clock

Trilateration Example:
3 Transmitters, 1 Receiver

- *Measurement of range requires precise knowledge of the time the signal is transmitted from the satellite, and received at the receiver*
- *Range (ρ) or "time of flight" measurement performed using ranging code on the signal*

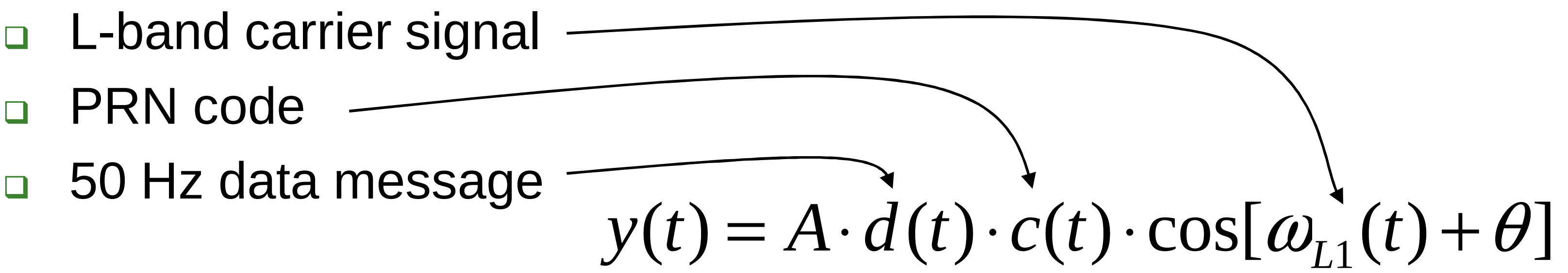

Receiver Location
ρ_3
T_3
ρ_2
ρ_1
T_1
T_2

Position Solution

- The position solution involves an equation with four unknowns:
  - Three components of receiver position (x, y, z)
  - Receiver clock bias
    - Position accuracy of ~1 m implies knowledge of the receiver clock to within ~3 ns
- Requires simultaneous measurements from four satellites
  - The receiver makes a range measurement to the satellite by measuring the signal propagation delay
  - Data message modulated on the ranging signal provides:
    - precise location of the satellite
    - corrections for errors in the satellite clock

GPS is a Spread-Spectrum Communications System

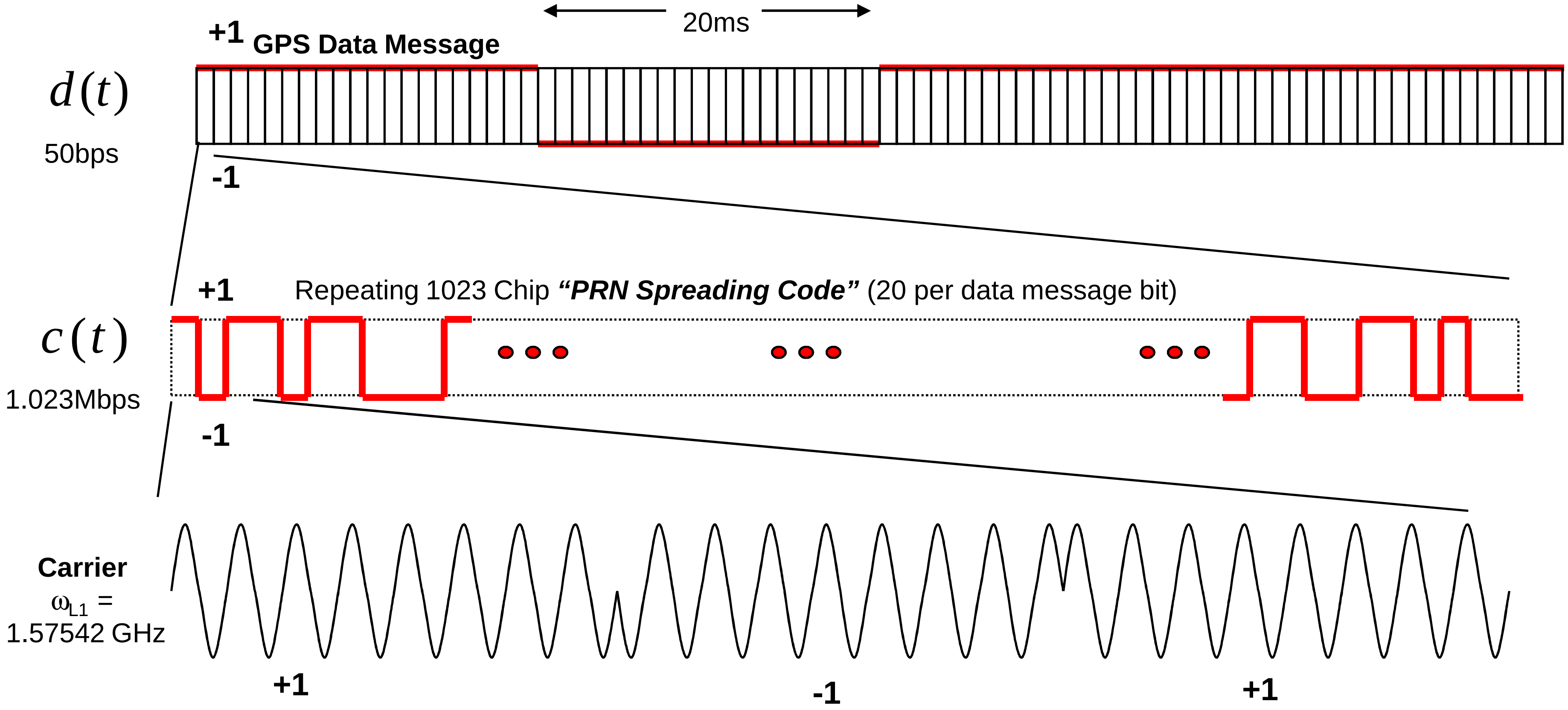
- Uses Code Division Multiple Access (CDMA):
  - Each satellite assigned a unique Pseudo-Random Noise (PRN) Code
  - All satellites transmit at the same frequency
- The power associated with the transmitted data is “spread” over a wide frequency band
- The received power is very low (below ambient noise levels)
- The transmitted signal is the combination of three signals:



  - L-band carrier signal
  - PRN code
  - 50 Hz data message

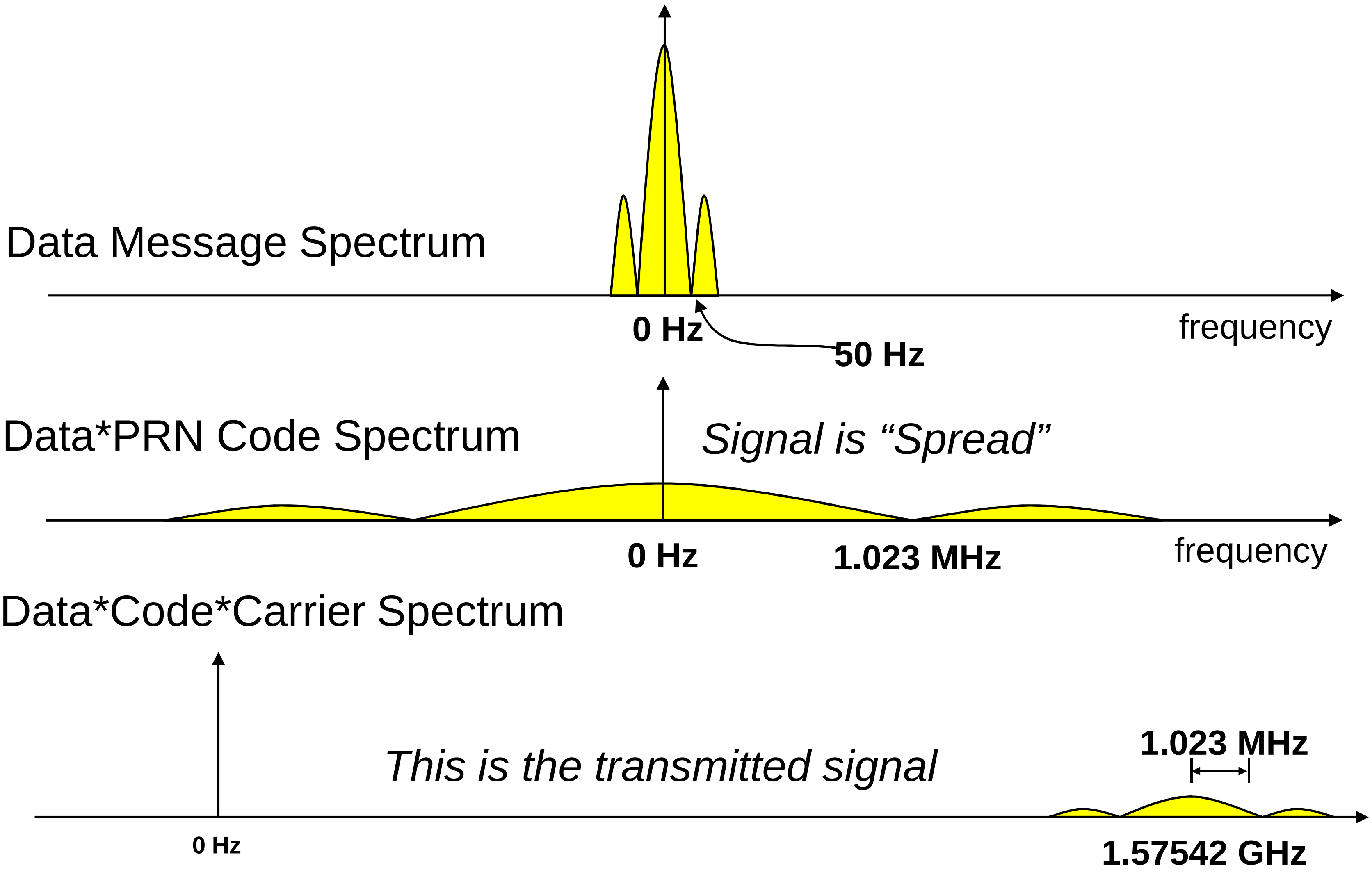
$$y(t) = A\cdot d(t)\cdot c(t)\cdot\cos[\omega_{L1}(t)+\theta]$$

GPS L1 C/A Signal (Time Domain)


20ms
+1
GPS Data Message
$d(t)$
50bps
-1
+1
Repeating 1023 Chip ***"PRN Spreading Code"*** (20 per data message bit)
$c(t)$
1.023Mbps
-1
Carrier
ω_{L1} =
1.57542 GHz
+1
-1
+1

$$y(t) = A \cdot d(t) \cdot c(t) \cdot \cos[\omega_{L1} t + \theta]$$

GPS L1 C/A Signal (Frequency Domain)



1. Data Message Spectrum

0 Hz

50 Hz

frequency

2. Data*PRN Code Spectrum

Signal is “Spread”

0 Hz

1.023 MHz

frequency

3. Data*Code*Carrier Spectrum

This is the transmitted signal

1.023 MHz

0 Hz

1.57542 GHz

GPS Receiver Acquisition and Tracking

- To detect the GPS signal and recover the navigation data, the receiver must produce a replica of the GPS signal with the correct time delay and Doppler to mix with the incoming signal
    - PRN codes for satellites are known
    - Receiver performs a search across possible time delays and Doppler shifts to acquire the signal
- GPS measurements are derived from the values of the PRN code phase (time delay) and carrier Doppler shift necessary to produce a large correlation with the incoming signal
    - Products of the receiver signal tracking loops

GPS Measurement Equation

- The GPS pseudorange measurement reaching the receiver, y_R has several changes:

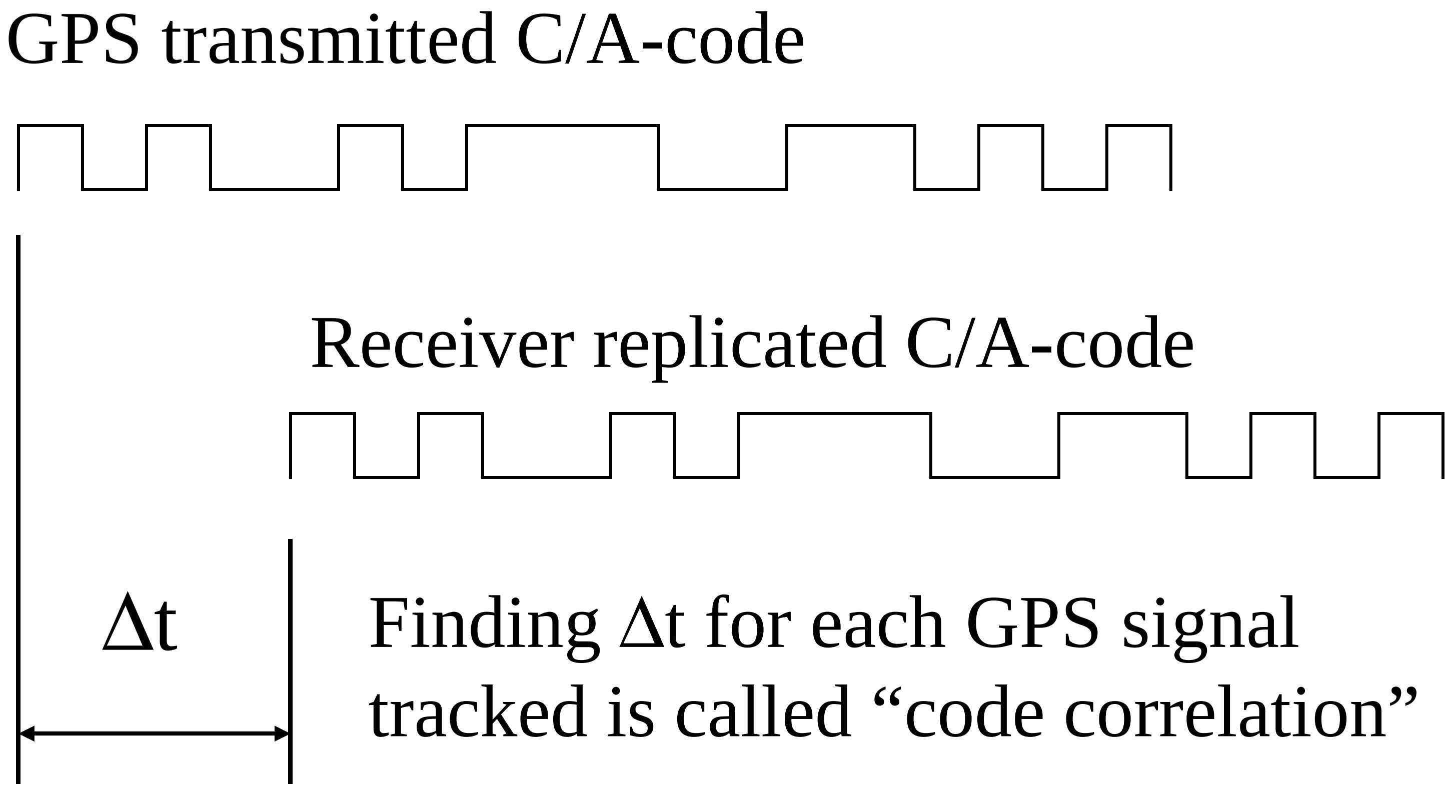
$$y_R(t) = A_R \cdot d(t-\tau) \cdot c(t-\tau) \cdot \cos\left[(\omega_{L1} + \omega_d)(t-\tau) + (\theta + \delta\theta)\right] + n$$

  - Time-delay, τ
  - Doppler frequency shift, ω_d
  - Phase shift, $\delta\theta$
  - Amplitude of received signal, A_r
  - Wideband noise, n

GPS Observables

- **GPS receivers typically report the following measurements**
  - Pseudorange
    - Propagation delay measured using the transmitted PRN code
  - Doppler
    - Measured frequency shift of the received carrier signal
  - Carrier Phase
    - Measured by counting accumulated cycles of the carrier signal
  - C/N_0
    - Carrier to noise spectral density (dB-Hz)

Pseudorange



GPS transmitted C/A-code

Receiver replicated C/A-code

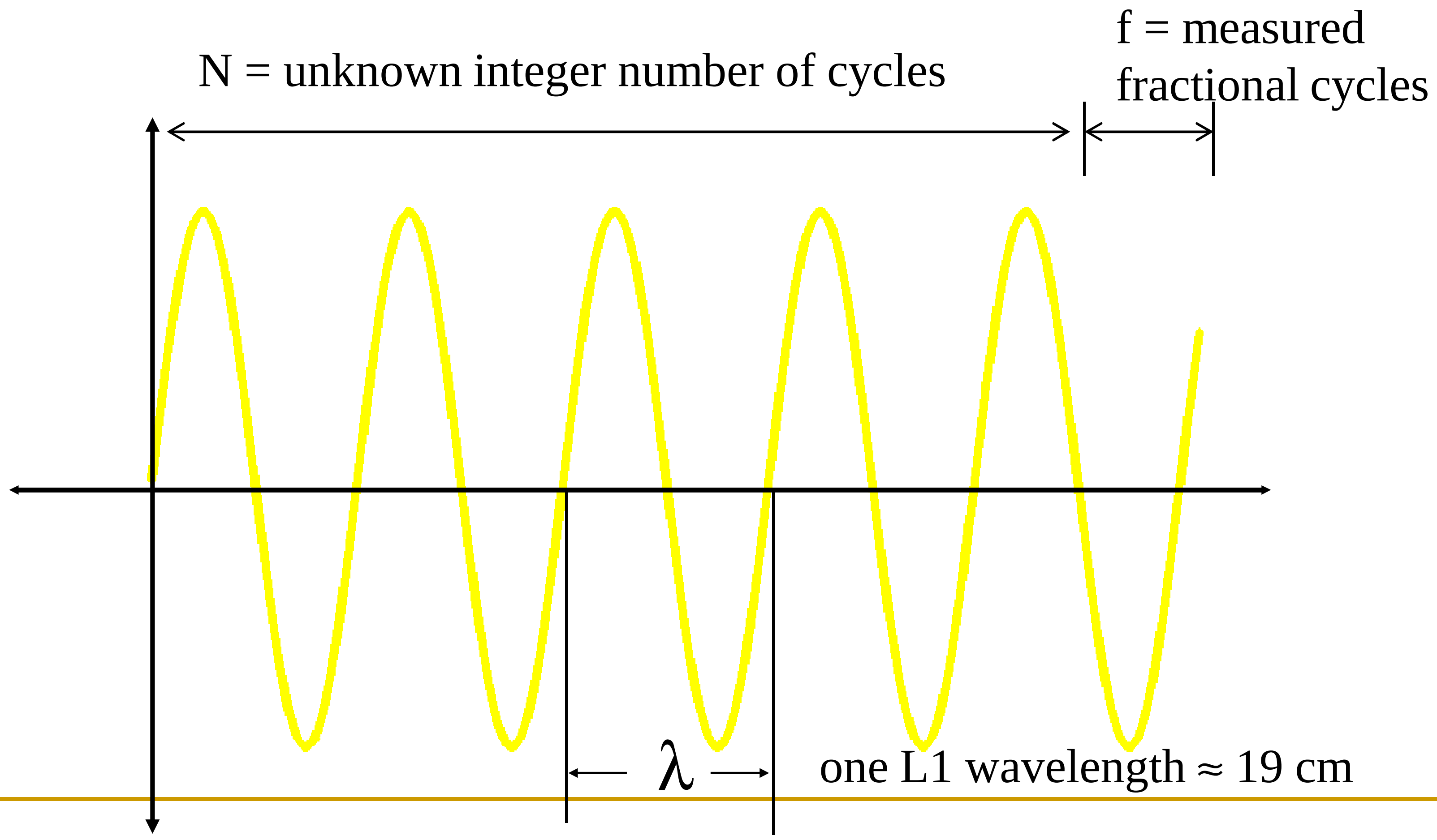
Δt

Finding Δt for each GPS signal tracked is called “code correlation”

- Δt is proportional to the GPS-to-receiver range
- Four pseudorange measurements can be used to solve for receiver position

Carrier Phase

The Doppler-shifted GPS carrier signal is mixed with the receiver reference signal to produce a beat wave whose phase can be measured with mm-level precision

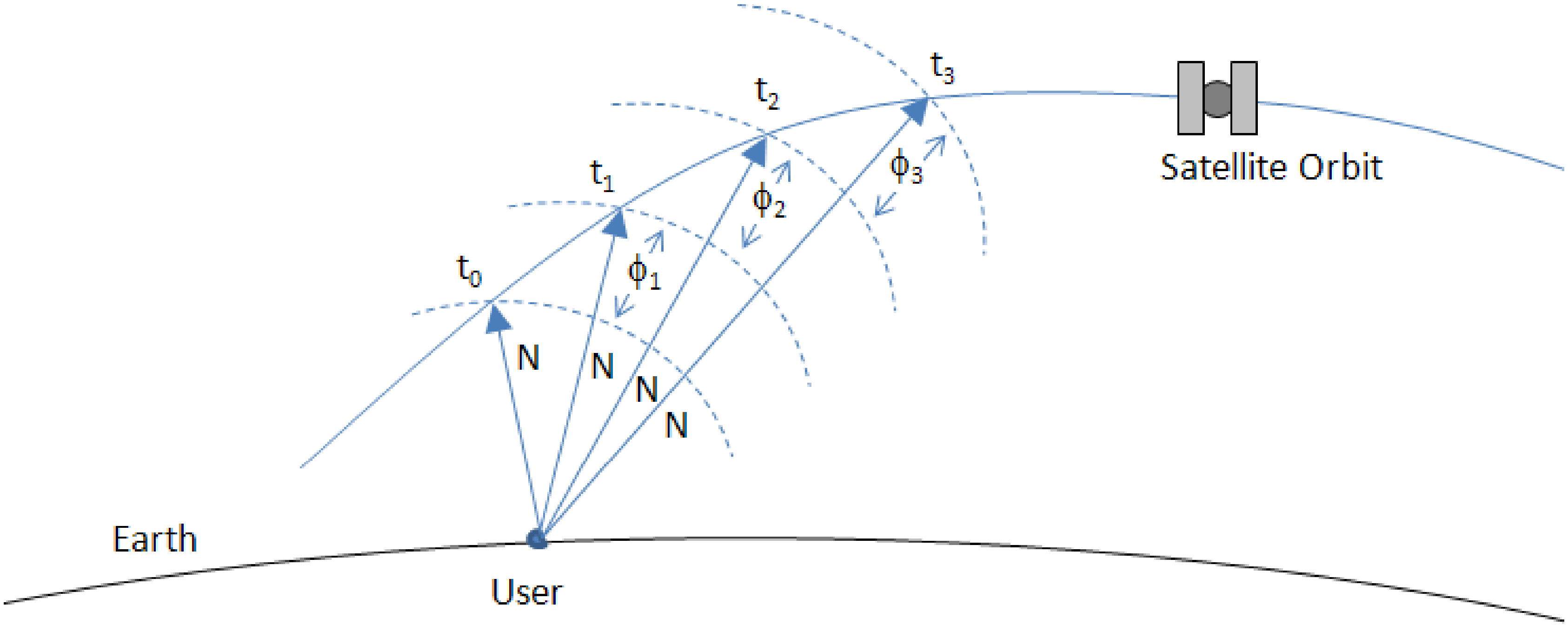


N = unknown integer number of cycles

f = measured fractional cycles

λ one L1 wavelength ≈ 19 cm

Carrier Phase Geometric Relationships


t0
t1
t2
t3
Satellite Orbit
ϕ1
ϕ2
ϕ3
N
N
N
N
Earth
User

- The overall phase measurement contains unknown number of carrier cycles
  - N is the carrier cycle ambiguity
- Advance in the carrier cycles since acquisition can be accurately counted
  - ϕ is the accumulated phase at the epoch shown

Measurement Equation (cont)

- Measured pseudorange to a satellite, k comprises:

$$\rho_k = \left\| \mathbf{r_k} - \underbrace{\mathbf{r}}_{} \right\| + c\left[\underbrace{\delta t}_{} - \delta t_k \right] + I_k + T_k + \varepsilon_k$$

- Receiver position and clock error solved for in GPS solution

  - true range (satellite position, r_k, known)
  - satellite clock error (δt_k, known)
  - ionosphere and troposphere delays (I_k, T_k, estimated or measured)
  - other errors (ε_k, satellite ephemeris and clock mis-modeling, measurement errors, multipath, receiver noise)

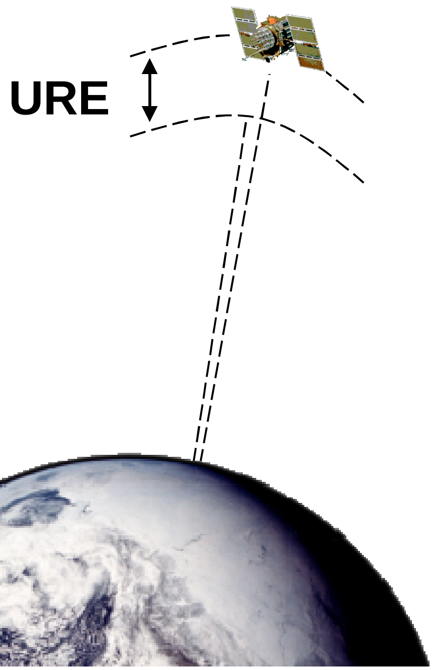
Solution Accuracy

- Two primary factors affect the fundamental position and time accuracy possible from the system:
    - Ranging error – a function of the quality of the broadcast signal and data
    - Geometry – the distribution of satellites in the sky

- The *actual* positioning accuracy achieved depends on system performance plus many other factors:
    - The design of the receiver (receiver/antenna noise levels, modeling errors, etc.)
    - Environmental effects such as ionosphere and troposphere signal delays, field of view obstructions, multipath signals, and jamming/interference.

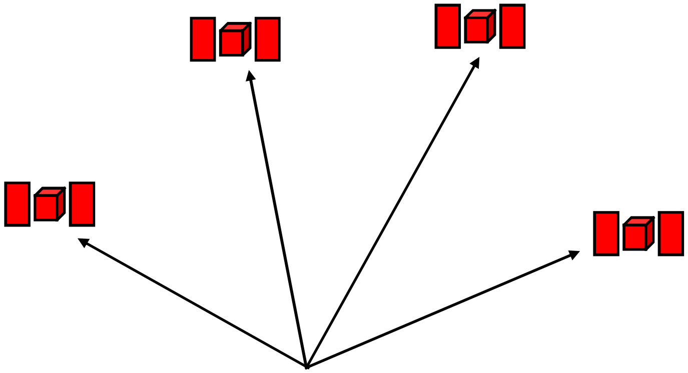
Ranging Error

- User Range Error
  - Signal-In-Space User Range Error (URE) is the difference between a GPS satellite's navigation data (position and clock) and the truth, projected on the line-of-sight to the user.
  - Indication of signal quality for an individual satellite
- Composite of several factors
  - stability of particular satellite's clock
  - predictability of the satellite's orbit

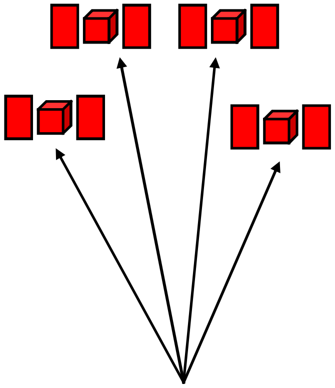


Geometry – Dilution of Precision

- Geometric Dilution of Precision (GDOP) is a measure of the quality of the receiver-to-GPS satellite range geometry
    - Related DOPs exist for position, horizontal, vertical, and time dilutions of precision
- Used in conjunction with the URE to forecast navigation and timing performance, weight measurements
- For GPS, DOP can range from 1 to infinity, with values in the 2-3 range being typical for GPS



Good GDOP



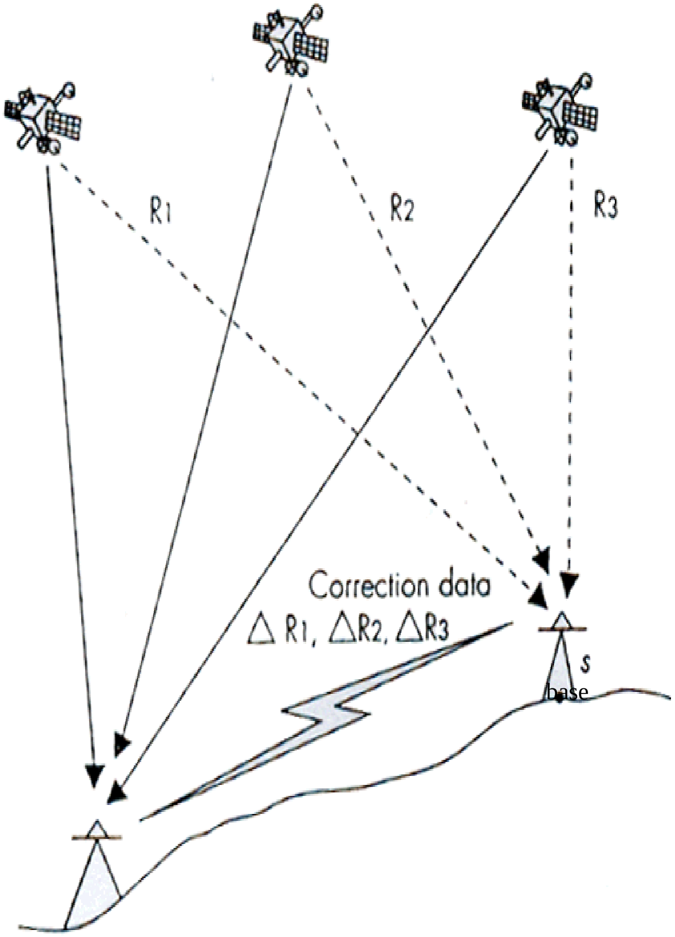
Poor GDOP

Typical Error Budget (Based on GPS)

Error Source	Typical Error
Ionosphere (< 1000 km)	1-5 m (single frequency, using broadcast model)
Troposphere (< 20 km)	0.1-1 m
GPS orbits	2.0 m (RMS)
GPS clocks	2.0 m (RMS)
Multipath (“clean” environment)	0.5-1 m code 0.5-1 cm carrier
Receiver Noise	0.25-0.5 m (RMS) code 1-2 mm (RMS) carrier

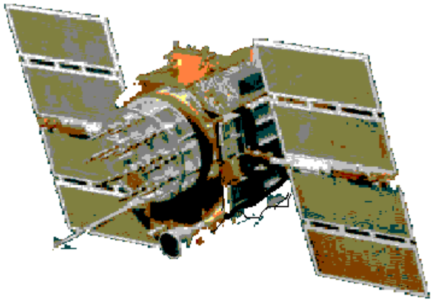
Differential Techniques

- **Receivers in close proximity can have their common error sources cancel**
  - Ionosphere and troposphere delays
  - Satellite orbit error
  - Satellite clock error
- **Single Differences (SD)** – formed from like measurements of the same GPS satellite made from two receivers
  - Removes errors common to both receivers
- **Double Differences (DD)** – formed by differencing two SD measurements from the same satellite
- **Fixed Base Station**
  - Broadcast corrections from a base station at a known location



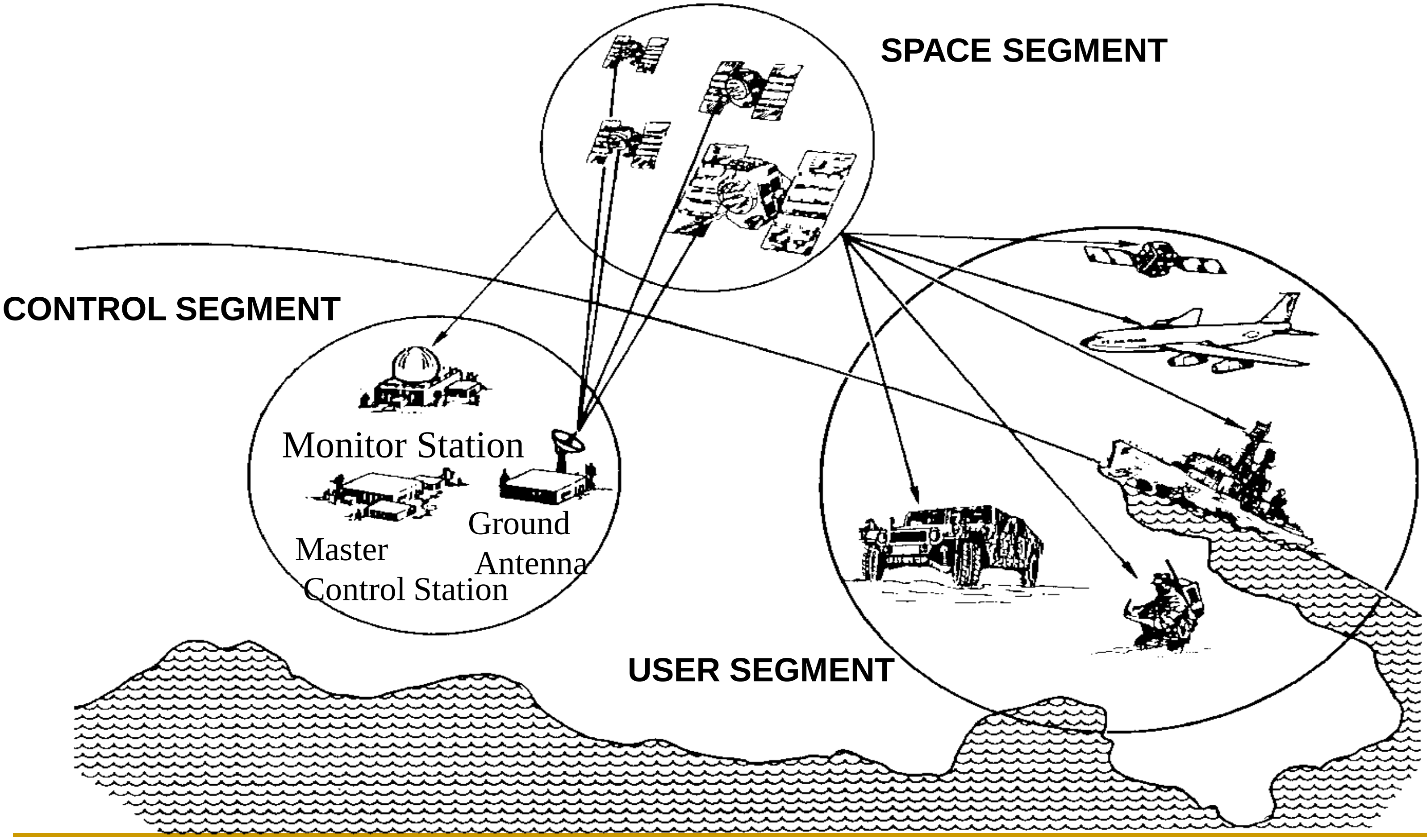
The US Global Positioning System (GPS) - History, Status, and Future

GPS History

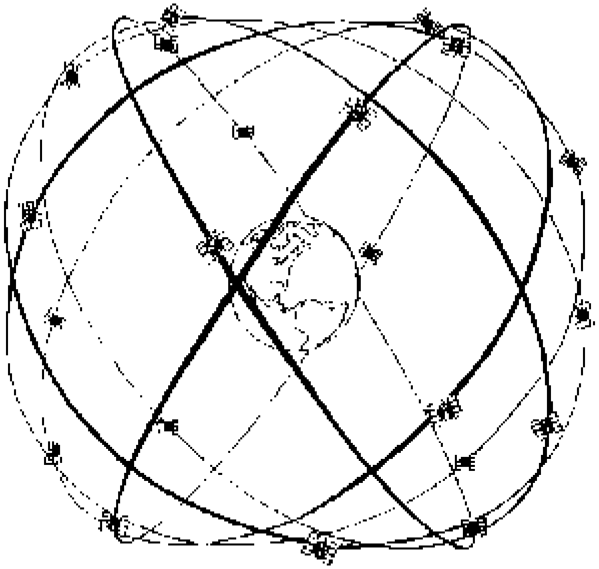


- Developed by the US Department of Defense
  - Early GPS program driver was Trident Missile Program (Submarine launched ICBM)
  - Satellites carry a nuclear detonation detection payload
- Early Satellite Navigation Systems
  - TRANSIT
  - Timation (first atomic frequency standards flown in space)
  - USAF 621B Program (use of PRN codes for ranging)
- First prototype GPS satellite launched in 1978
- First Block II (Operational) GPS satellite launched 1989
- Full Operational Capability declared in 1994
- First in series of “modernized” GPS satellites began launching in 2005

GPS System Configuration – Three Segments


SPACE SEGMENT
CONTROL SEGMENT
Monitor Station
Ground Antenna
Master Control Station
USER SEGMENT

GPS Space Segment

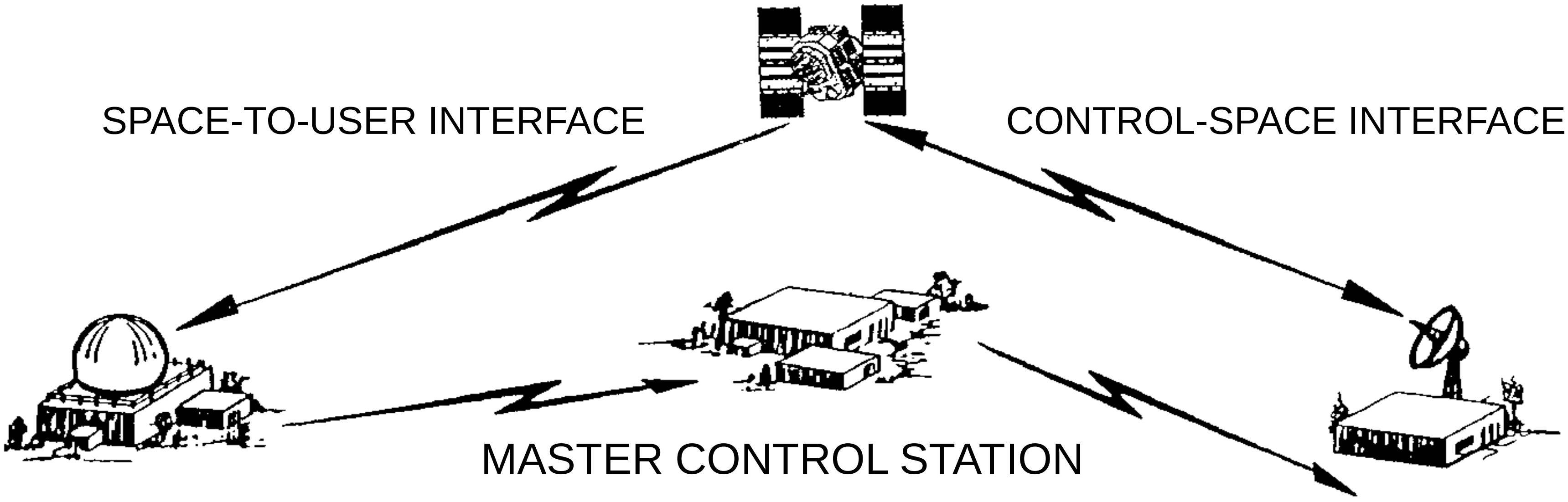


- Nominal 24 satellite constellation
  - Semi-synchronous, circular orbits (~20,200 km/10,900 nautical miles altitude)
  - Repeating ground tracks (11 hours 58 minutes)
  - Six orbital planes, inclined at 55 degrees, four vehicles per plane
    - *Designed for global coverage (at least 4 sats in view)*
- Redundant cesium and/or rubidium clocks on board each satellite
- Until recently there have been 2-3 replenishment launches per year

GPS Control Segment

SPACE VEHICLE

Broadcasts the Signal in Space (SIS) PRN codes, L-band carriers, and 50 Hz navigation message (stored in memory)



SPACE-TO-USER INTERFACE

CONTROL-SPACE INTERFACE

MASTER CONTROL STATION

- Checks for anomalies
- Computes SIS portion of URE
- Generates new orbit and clock predictions
- Builds new upload and sends to GA

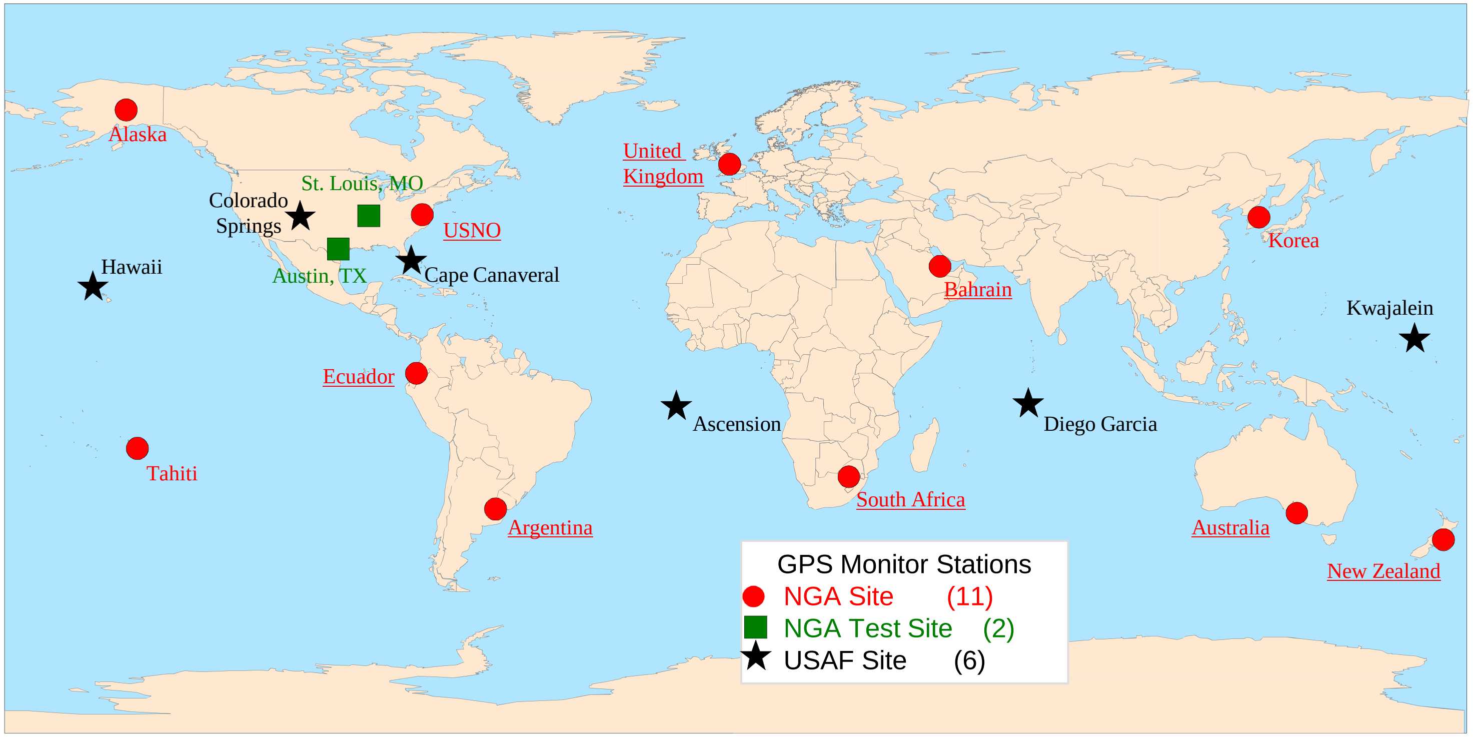
MONITOR STATION

- Sends raw observations to MCS

GROUND ANTENNA

- Sends new upload to SV

Control Segment – Monitor Stations


Alaska
United Kingdom
St. Louis, MO
Colorado Springs
USNO
Korea
Hawaii
Austin, TX
Cape Canaveral
Bahrain
Kwajalein
Ecuador
Ascension
Diego Garcia
Tahiti
South Africa
Argentina
Australia
New Zealand
GPS Monitor Stations
● NGA Site (11)
🟩 NGA Test Site (2)
★ USAF Site (6)

- U.S. Air Force GPS Monitor Stations:
  - Hawaii, Ascension Island, Diego Garcia, Kwajalein, Cape Canaveral, and Colorado Springs
- National Geospatial-Intelligence Agency (NGA) monitor stations incorporated into Control Segment Kalman filter solution as part of Legacy Accuracy Improvement Initiative

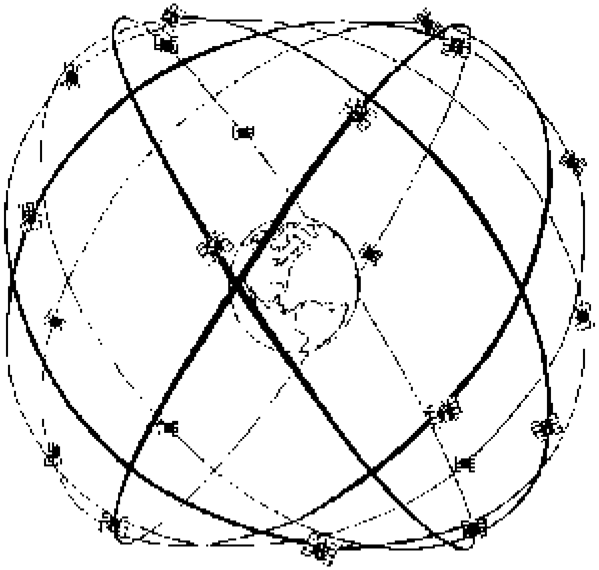
GPS User Segment

- GPS receivers are specialized “radios” that track GPS signals and produce position and velocity solutions
  - Wide range of cost/sophistication depending on the application
- Signals from 4 or more GPS satellites are required, but 8-10 are typically available at any time
- Low cost civil (SPS) receivers typically track only the L1 C/A signal
- PPS receivers have special keys that allow tracking of the military P(Y) code over both L1 and L2
- Higher performance civil receivers use cross-correlation techniques to track codes on L2 and will also track L2C.

Military Spacecraft
(~$1,000,000)

Consumer Recreation
(~$100-500)

Legacy GPS Signal Structure



- **Two L-band carrier frequencies**

  L1 = 1575.42 MHz   L2 = 1227.60 MHz
- **Two PRN Codes – Uniquely Identify Each Satellite**
  - C/A: Coarse Acquisition (Civilian) Code
    - Broadcast only on L1 carrier
    - Available to all users
    - One millisecond repeat interval
  - P(Y): Military Code
    - Y code is encrypted version of P code – code sequence not published
      - Only available to authorized (military users)
    - 267 day repeat interval
    - Available on both L1 and L2 carriers
- **Code modulated with Navigation Message Data**
  - Provides ephemeris data and clock corrections for the GPS satellites
  - Low data rate (50 bps)

GPS Modernization - Goals

- System-wide improvements in:
    - Accuracy
    - Availability
    - Integrity
    - Reliability
- Robustness against interference
- Improved indoor, mobile, and urban use
- Interoperability with other GNSS constellations
- Backward compatibility

New Civil Signals

L2C

Second civil signal

- Designed to meet commercial needs
- Higher accuracy through ionospheric correction
- 1st launch: Sep 2005 (GPS IIR-M); **24 satellites: ~2016**

Benefits existing professional receivers

L5

Third civil signal

- Designed to meet demanding requirements for transportation safety-of-life
- 1st launch: May 2010 (GPS IIF); **24 satellites: ~2018**

L1C

Fourth civil signal

- Designed with international partners for GNSS interoperability
- More robust across broad range of applications
- Begins with GPS III
- 1st launch: ~2014 (GPS III); **24 satellites: ~2021**

Under trees

Urban Canyons

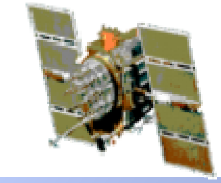
Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010

GPS Modernization Programs

Space Segment

1995

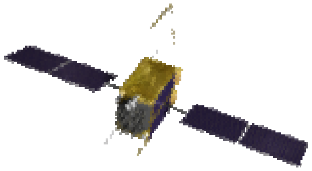
GPS IIA/GPS IIR



- Standard Positioning Service (SPS)
  - o Single frequency (L1) coarse acquisition code navigation
- Precise Positioning Service (PPS)
  - o Y-Code (L1 P(Y) & L2 P(Y))

2005

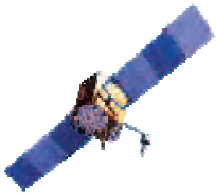
GPS IIR-M



- IIA/IIR capabilities plus:
  - o 2nd civil signal (L2C)
  - o M-Code (L1M & L2M)

2010

GPS IIF



- IIR-M capability plus
  - o 3rd civil signal (L5)
  - o 12 year design life

2014 - 2025

GPS III

- Backward compatible
- 4th civil signal (L1C)
- Increased accuracy
- Increased integrity
- Increased design life

Ground Control Segment

Legacy Control System

Architecture Evolution Plan (AEP)

Next Generation Control Segment (OCX)

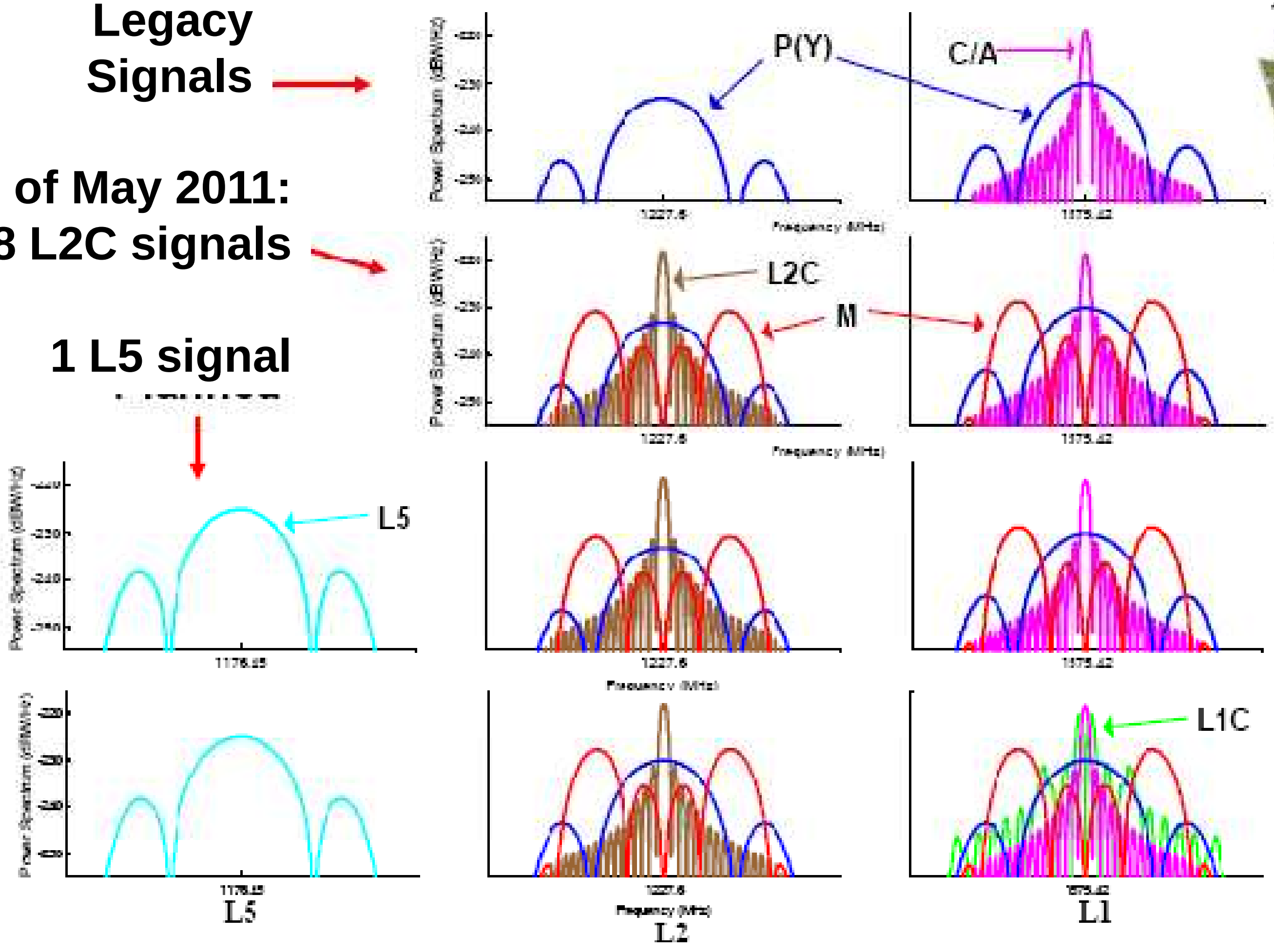
Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010

GPS Modernization – Spectrum

Legacy Signals

**As of May 2011:
8 L2C signals**

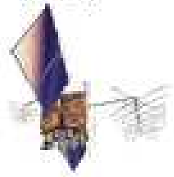
1 L5 signal



ARNS Band *RNSS Band* *ARNS Band*

Block IIA
1990

Block IIR
1997



Block IIR-M, 2005

Block IIF, 2010

Block III, 2014

(artist's concept)

Presented by Col Mark Crews, ION National Technical Meeting, January, 2008.

GPS Modernization – Ground

- **Architecture Evolution Plan (AEP)**
  - Transitioned in 2007
  - Modern distributed system replaced 1970's mainframes
  - Increased capacity for monitoring of GPS signals to 100% worldwide coverage (was 96.4%) and have 99.8% of world double covered
  - Increased worldwide commanding capability from 92.7% to 94.5% while providing nearly double the backup capability

- **Next Generation Operational Control Segment (OCX)**
  - Enables modernized messaging
  - Controls more capable GPS constellation
  - $1.53B contract awarded February 2010

Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010

Current GPS Constellation Status

- **31 space vehicles currently in operation**
  - **11 GPS IIA**
  - **12 GPS IIR**
  - **7 GPS IIR-M**
  - **1 IIF**
  - **3 additional satellites in residual status**
  - **1 additional IIR-M waiting to be set healthy**
- **Next launch expected: June 2011**
- **Continuously assessing constellation health to determine launch need**
- **Global GPS civil service performance commitment met continuously since Dec 1993**

Block II/IIA
Built by Boeing Aerospace
Launched 1989 - 1997

Block IIR/IIR-M
Built by Lockheed Martin
Launched 1997 - 2009

Block IIF
Built by Boeing Aerospace
First Launch in 2010

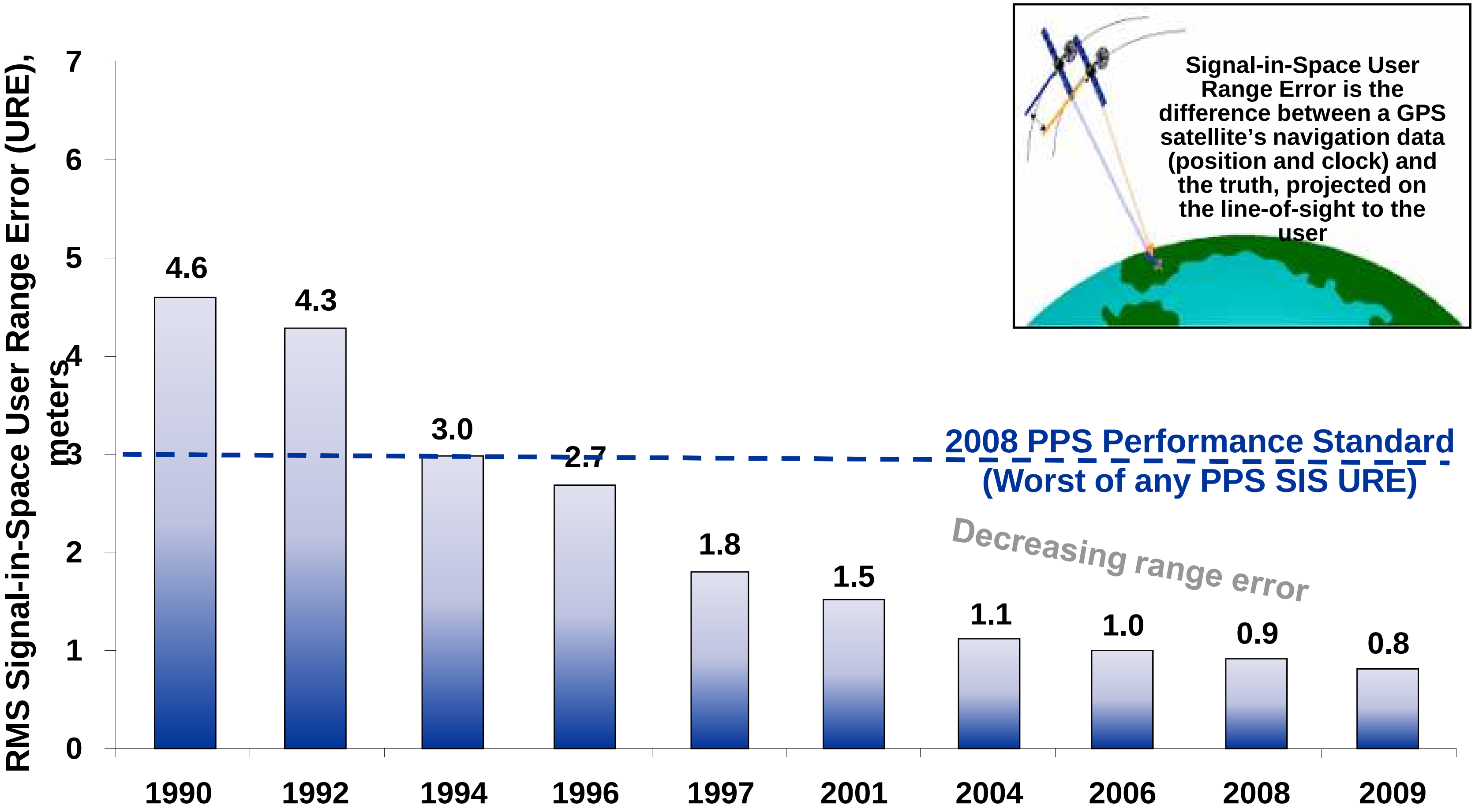
Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010

Performance Standards

- **The AF, DoD, and U.S. Government are committed to being good stewards of GPS**
- **The GPS Standard Positioning Service (SPS) Performance Standard defines the levels of performance the U.S. Government commits to provide civil GPS users**
  - Precise Positioning Service (PPS) Performance Standard for military
- **Documents updated periodically to reflect service improvements**
- **GPS SPS Performance Standard (Sep 2008) available on US Coast Guard Navigation Center website**
  - http://www.navcen.uscg.gov/

Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010

PPS Signal in Space Performance

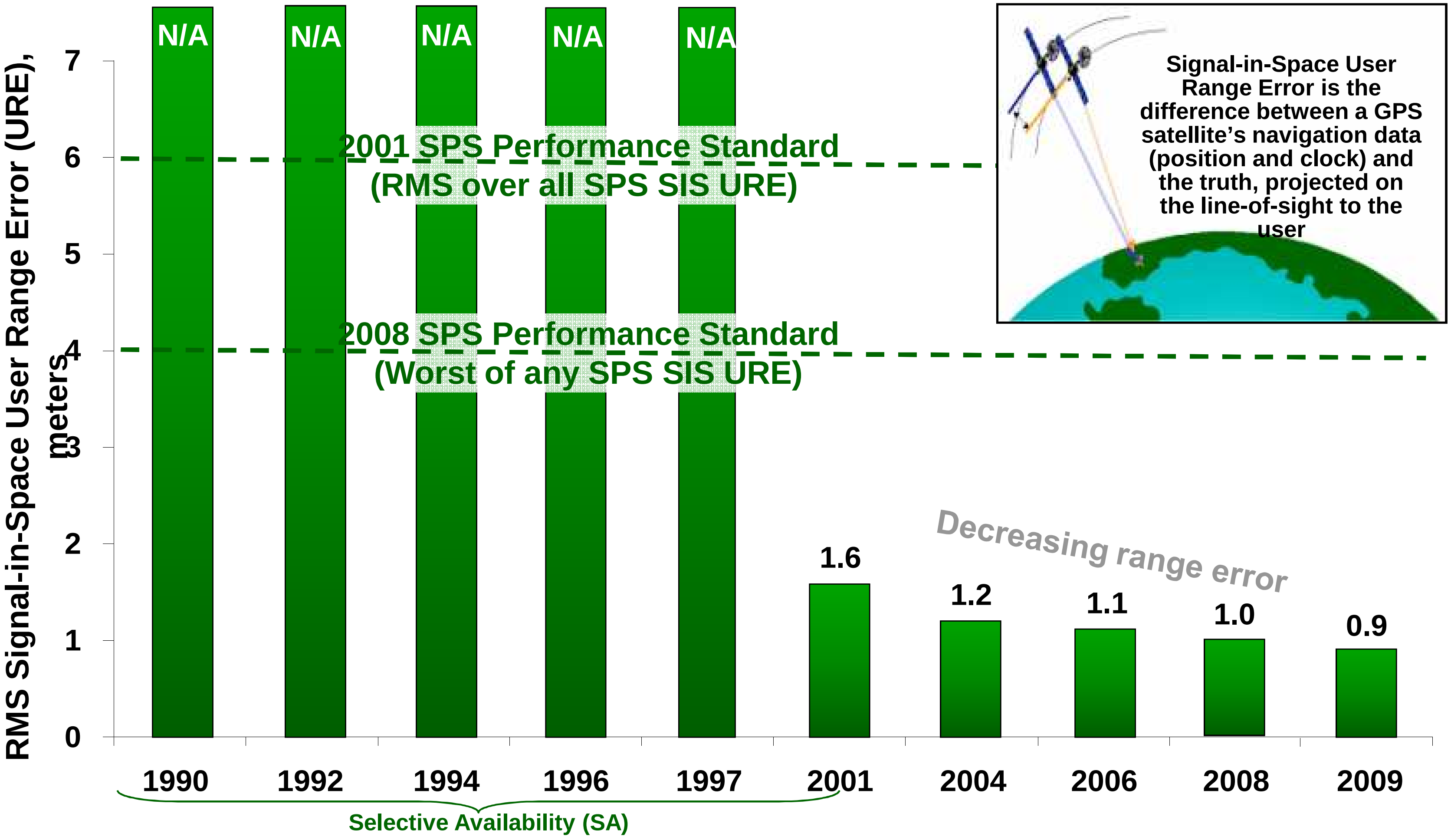


Signal-in-Space User Range Error is the difference between a GPS satellite’s navigation data (position and clock) and the truth, projected on the line-of-sight to the user

System accuracy exceeds published standard

Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010

SPS Signal in Space Performance



Signal-in-Space User Range Error is the difference between a GPS satellite's navigation data (position and clock) and the truth, projected on the line-of-sight to the user

System accuracy exceeds published standard

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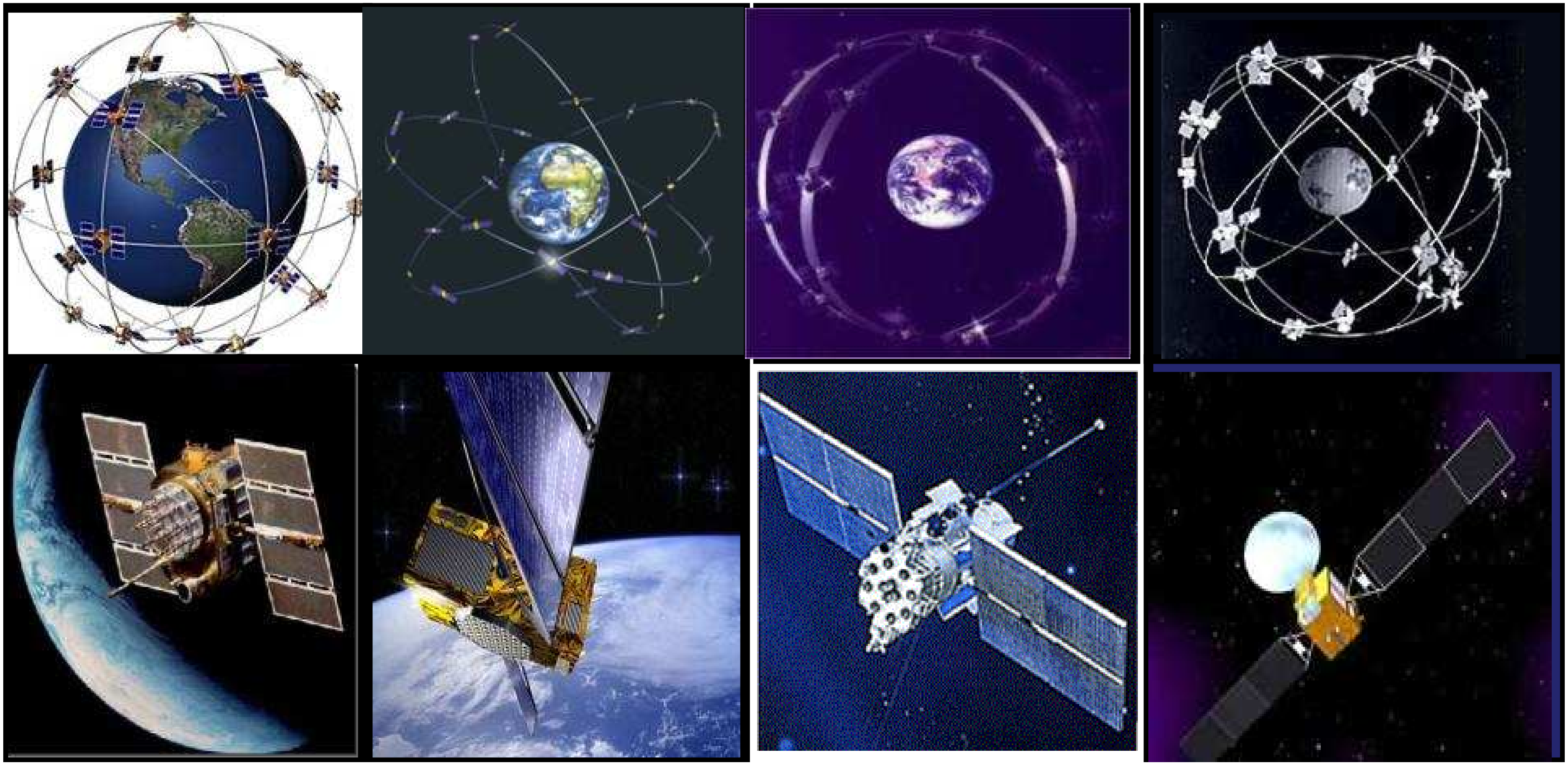
Other GNSS Systems and Augmentations

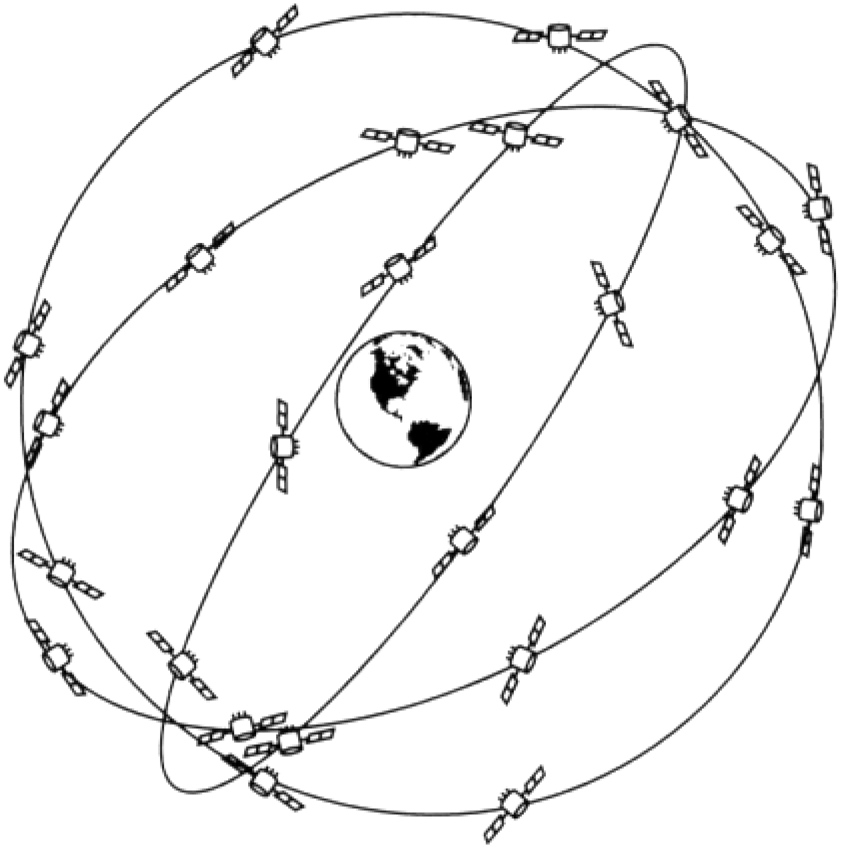
Global GNSS Constellations

GPS	Galileo	GLONASS	Beidou/Compass
US	EU	Russia	China
(24+)	(27)	(24)	(35)



GLONASS: GLObal NAvigation Satellite System

РОСКОСМОС



GLONASS Satellite Constellation

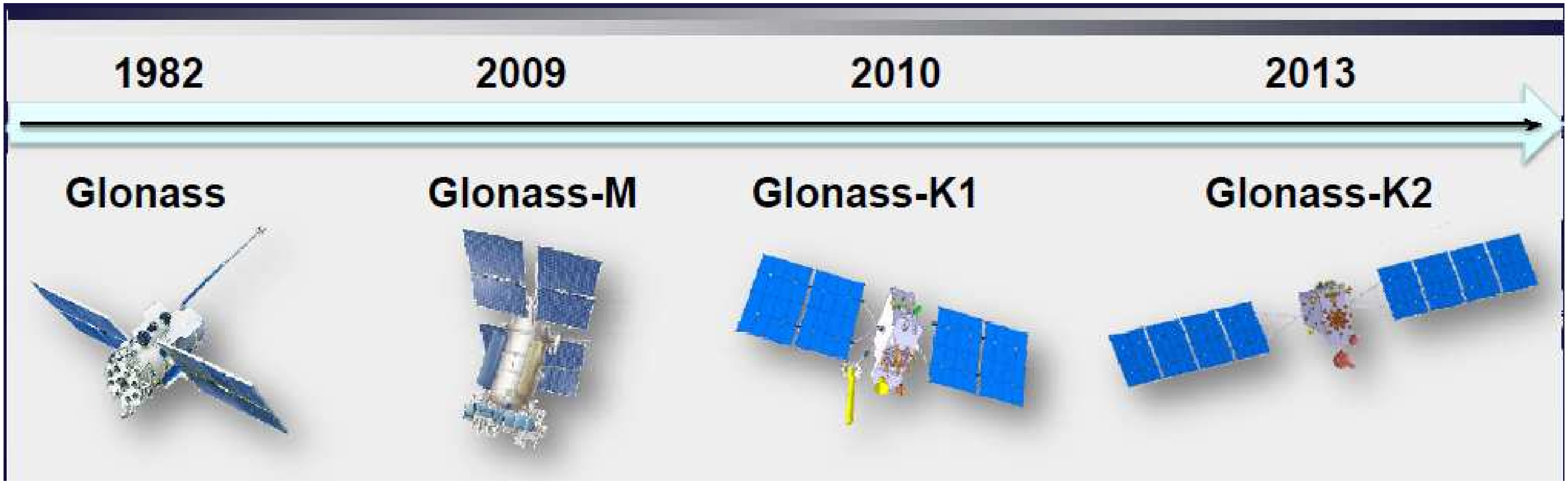
- Radio-based satellite navigation system operated by the Russian Space Forces
- 24 satellites in 3 orbital planes
- Each satellite transmits signal on unique frequency (FDMA)
- First satellite launched in 1982
- System fell into disrepair with collapse of Soviet Union
- Replenishment and modernization of the constellation made a top priority under the Putin Presidency
- Constellation Status:
  - http://www.glonass-ianc.rsa.ru/en/

GLONASS Status

- GLONASS Constellation Status (2 May 2011)
    - 27 Total satellites in constellation
    - 22 Operational
    - 1 In Commissioning Phase
    - 4 In Maintenance
- Most recent launch in Dec 2010:
    - ❑ Three GLONAAS M satellites failed to reach orbit due to a failure in the launch vehicle upper stage
- Nominal constellation of 24 operational satellites expected by the end of 2011
- GLONASS accuracy has improved significantly over the past five years; approaching performance of GPS

GLONASS Modernization

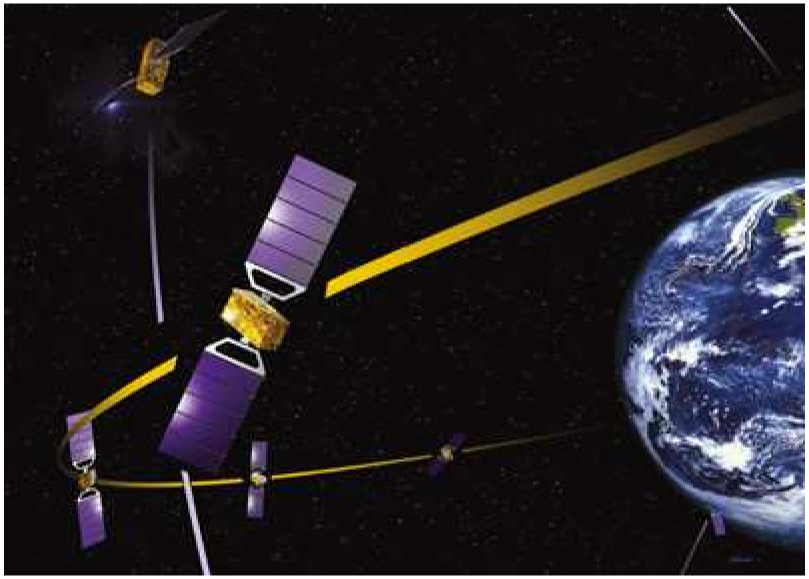
- GLONASS modernization efforts include:
  - Introduction of new CDMA signals for improved interoperability with other GNSS systems
  - Continue to broadcast legacy FDMA signals
  - New GLONASS K satellites with improved accuracy and longer design life
  - Improvements to ground control system


1982
2009
2010
2013
Glonass
Glonass-M
Glonass-K1
Glonass-K2

For more information, see: GLONASS Status and Progress, Sergey Revnivykh, 21 September 2010
http://www.navcen.uscg.gov/pdf/cgsicMeetings/50/%5B3%5DCGSIC_GLONASS_Revnivykh_20_09_2010.pdf

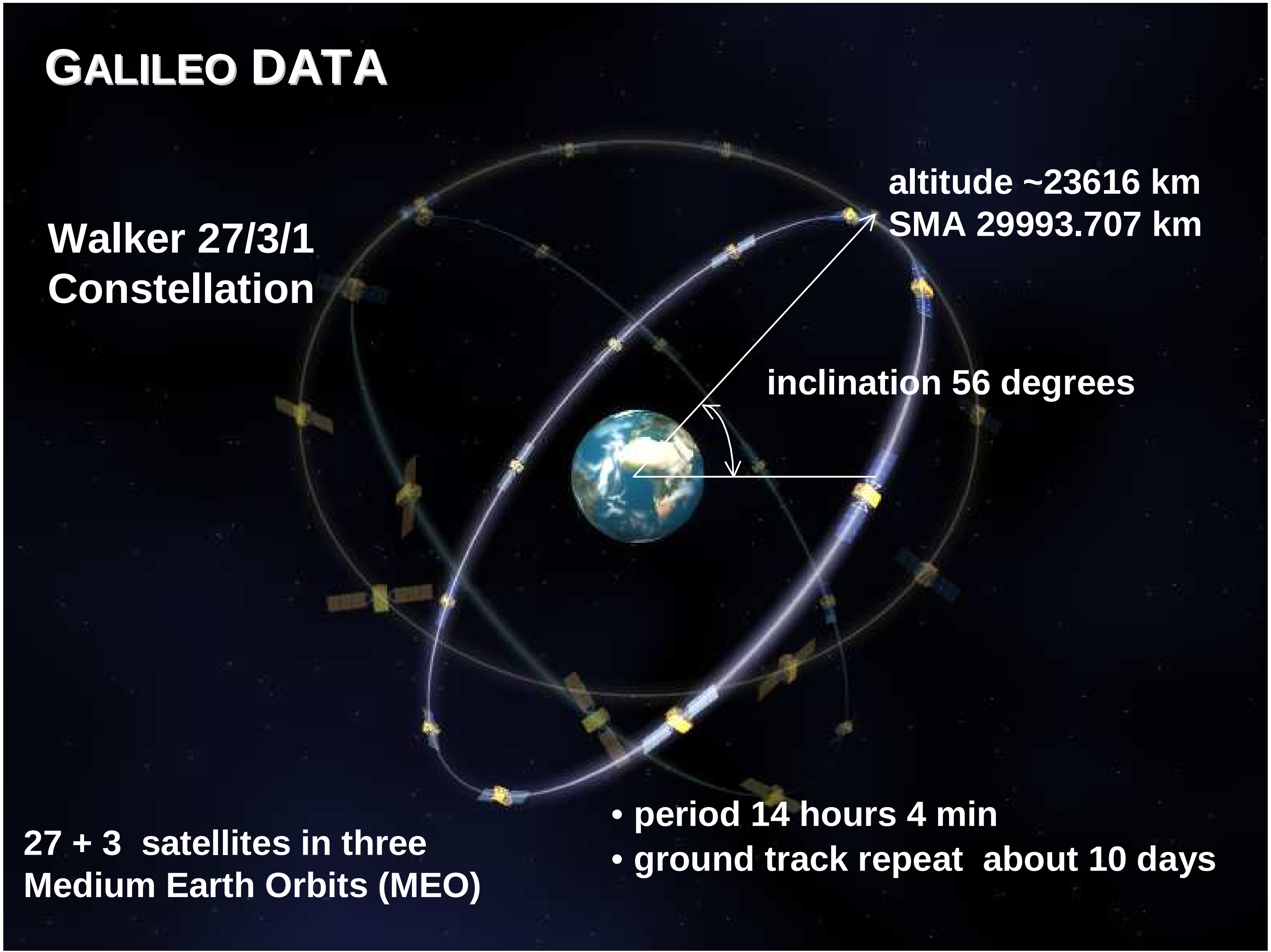
GALILEO

- Galileo is a joint initiative of the European Commission (EC) and the European Space Agency (ESA).
- It will be interoperable with GPS and GLONASS, the two other global satellite navigation systems.
- Consists of 30 medium Earth orbit satellites, associated ground infrastructure, and regional/local augmentations.
- Will offer a basic service for free (Open Service), but will charge user fees for premium services.



http://www.esa.int/esaNA/galileo.html

Galileo Constellation Configuration



GALILEO DATA

Walker 27/3/1
Constellation

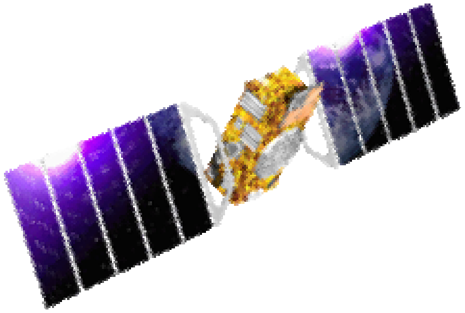
altitude ~23616 km
SMA 29993.707 km

inclination 56 degrees

- period 14 hours 4 min
- ground track repeat about 10 days

27 + 3 satellites in three
Medium Earth Orbits (MEO)

Galileo Implementation Plan



Full Operational Capability
27 (+3) Galileo satellites
>2014

In-Orbit Validation
4 IOV satellites plus
ground segment
2011

Galileo System Testbed v2
2 initial test satellites
2005

GALILEO
GIOVE

Galileo System Testbed v1
Validation of critical algorithms
2003

GALILEO
GSTB-V1

From “**European GNSS Programmes EGNOS and Galileo**,” Paul Verhoef

Chinese Compass System

- In 2006 China announced plans to develop a 35-satellite, global navigation system
- The **Compass** system (also known as **BeiDou**) will include 5 geostationary orbit (GEO) satellites and 30 medium Earth orbit (MEO) satellites
- BeiDou will provide three carrier frequencies foreseen to be interoperable with other systems.
- Demonstration Phase – completed in 2003 with launch of 3 Geostationary satellites
- Second Phase (BeiDou-2) – provision of satellite navigation services for Asia-Pacific region
  - As of April 2011, eight BeiDou-2 satellites launched (latest 4/10/11)
  - More than ten satellites planned by 2012
  - System complete by 2020

http://www.beidou.gov.cn/

Regional Satellite Navigation Systems

- Indian Regional Navigational Satellite System (IRNSS)
  - Autonomous regional satellite navigation system consisting of 7 satellites and ground segment
  - Developed by Indian Space Research Organization
- Quasi-Zenith Satellite System (QZSS) – Japan
  - Will provide an augmentation service which, when used in conjunction with GPS, GLONASS or Galileo, will provide enhanced navigation in the Far East
  - Consists of three satellites in highly elliptical orbits - satellites dwell at high elevations in the sky allowing enhanced coverage in urban canyons.

Satellite-Based Augmentation Systems (SBAS)

- **Wide Area Augmentation System (WAAS)**
  - Commissioned in 2003 and operated by the U.S. Federal Aviation Administration (FAA), to enable aircraft navigation in the U.S. National Airspace System (NAS)
- **European Geostationary Navigation Overlay System (EGNOS)**
  - Three geostationary satellites and a network of ground stations
  - Augments the US GPS satellite navigation system in Europe
- **Japan's Multifunction-Transport-Satellite Satellite Augmentation System (MSAS)**
  - MSAS for aviation use was commissioned in 2007
- **India's GPS and Geo-Augmented Navigation System (GAGAN) (operational in 2011)**
- **Russian System of Differential Corrections and Monitoring (SDCM) (operational in 2011)**

Other GPS Augmentations

- **Nationwide Differential GPS System (NDGPS):**
  - Ground-based augmentation system of ~80 sites operated by the U.S. Coast Guard, Federal Railroad Administration, and Federal Highway Administration, to provide increased accuracy and integrity to U.S. users on land and water.
- **Local Area Augmentation System (LAAS):**
  - Augmentation to GPS that focuses its service on the airport area (approximately a 20-30 mile radius)
  - Broadcasts correction message via a very high frequency (VHF) radio data link from a ground-based transmitter
  - LAAS is a US activity led by the FAA, but other nations are developing their own ground based augmentation system projects
- **NASA Global Differential GPS (GDGPS) System:**
  - GDGPS is a commercial high accuracy (~ 10cm) GPS augmentation system, developed by the Jet Propulsion Laboratory (JPL) to support real-time positioning, timing, and orbit determination requirements.

Radio Frequency Interference Concerns

- ***GPS Jamming Navigation: As the uses of satellite-positioning technology continue to grow, what can be done to stop deliberate and dangerous jamming of the signals? The Economist, Mar 10, 2011***
  - ❑ http://www.economist.com/node/18304246?story_id=18304246http://www.economist.com/node/18304246?story_id=18304246

- ***GPS Community Confronts LightSquared Move into L1 Spectrum, Inside GNSS, March/April 2011***
  - ❑ http://www.insidegnss.com/node/2508

Thank You.

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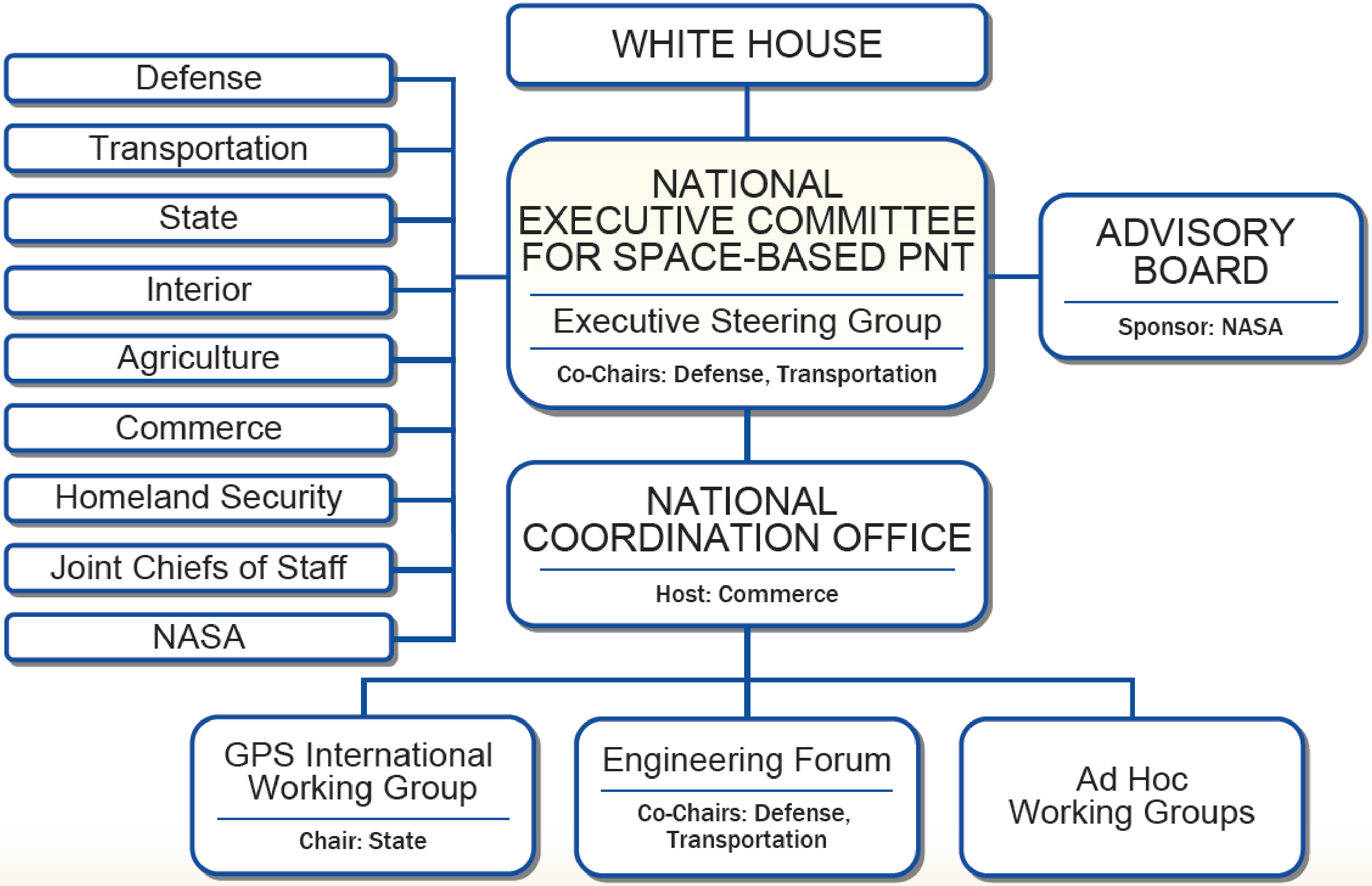
Backup Information and References

Subsequent charts provide additional information and references that could not be included in the presentation.

Acronyms and Definitions

AEP – GPS Architecture Evolution Program
ARNS – Aeronautical Radio Navigation Service spectrum band
CDMA – Code Division Multiple Access
C/A – GPS Course Acquisition Code
C/N0 - Carrier to Noise Spectral Density
COMPASS – Chinese Satellite Navigation System
CORS – Continuously Operating Reference Stations
DoD – Department of Defense
EC – European Commission
ESA – European Space Agency
FDMA – Frequency Division Multiple Access
Galileo – European Satellite Navigation System
GDGPS – NASA Global Differential GPS System
GDOP – Geometric Dilution of Precision
GNSS – Global Navigation Satellite Systems
GPS – US Global Positioning System
GLONASS – Russian GLObal NAvigation Satellite System
GST – Galileo System Time
GTRF – Galileo Terrestrial Reference Frame
IERS – International Earth Rotation Service
IGS – International GNSS Service
ITRS – International Terrestrial Reference System
LAAS – Local Area Augmentation System
L1 – GPS signals at 1.57542 GHz
L1C – New GPS code planned for L1 signal
L2 – GPS signals at 1.22760 GHz
L2C – New GPS code on L2 signal
L5 – New GPS signals at 1.17645 GHz
MEO – Medium Earth Orbit
NASA – National Aeronautics and Space Administration
NDGPS – Nationwide Differential GPS System
NIMA – National Imagery and Mapping Agency, currently known as National Geospatial-Intelligence Agency (NGA)
NIST – National Institutes of Standards and Technology
OCS – GPS Operational Control Segment
OCX – Next Generation GPS Operational Control Segment
PRN – Pseudo-Random Noise
PNT – Position, Navigation, and Timing
P(Y) – GPS precision code
QZSS – Japanese Quazi-Zenith Satellite System
RMS – Root Mean Square
RNSS - Radio Navigation Satellite Service spectrum band
SBAS – Space Based Augmentation System
TAI – International Atomic Time
USAF – United States Air Force
USNO – United States Naval Observatory
URE – User Range Error
UTC – Universal Coordinated Time
WAAS – Wide Area Augmentation System

U.S. Space-Based PNT Organizational Structure



WHITE HOUSE

Defense

Transportation

State

Interior

Agriculture

Commerce

Homeland Security

Joint Chiefs of Staff

NASA

NATIONAL EXECUTIVE COMMITTEE FOR SPACE-BASED PNT

Executive Steering Group

Co-Chairs: Defense, Transportation

ADVISORY BOARD

Sponsor: NASA

NATIONAL COORDINATION OFFICE

Host: Commerce

GPS International Working Group

Chair: State

Engineering Forum

Co-Chairs: Defense, Transportation

Ad Hoc Working Groups

2004 U.S. Space-Based Positioning, Navigation, and Timing Policy

- Recognizes the changing international scene
  - Other nations implementing space-based systems that provide PNT services
- National Space-Based PNT Executive Committee
  - Chaired by Deputy Secretaries of Defense and Transportation
  - Membership includes: State, Commerce, Homeland Security, JCS and NASA
- Established National Coordination Office (NCO) with staff from each member agency

GNSS Compatibility and Interoperability Objectives

- Ensure **compatibility** - ability of U.S. and non-U.S. space-based PNT services to be used separately or together without interfering with each individual service or signal
- Achieve **interoperability** – ability of civil U.S. and non-U.S. space-based PNT services to be used together to provide the user better capabilities than would be achieved by relying solely on one service or signal

GPS References

- B.W. Parkinson et al. (editors), *Global Positioning System: Theory and Applications*, Vol. 1&2, Progress in Astronautics and Aeronautics, 1997.
- E. Kaplan (editor), *Understanding GPS: Principles and Applications*, Artech House Publishers, 1996.
- P. Misra, P. Enge, *Global Positioning System: Signals, Measurements, and Performance*, Ganga-Jamuna Press, 2001.
- http://pnt.gov/
- http://gps.gov
- http://gps.faa.gov/index.htm
- US Coast Guard Navigation Center
  - http://www.navcen.uscg.gov/GPS/default.htm
  - http://www.navcen.uscg.gov/pubs/frp2001/
- NASA Global Differential GPS System
  - http://www.gdgps.net/

GLONASS

GLONASS Constellation

- 24 satellites in 3 orbital planes
  - ascending nodes 120 degrees apart
  - 8 satellites equally spaced in each plane
  - argument of latitude displacement of 45 degrees
  - planes have 15 degrees argument of latitude displacement
- Circular 19,100 km orbit
  - inclination angle of 64.8 degrees
- Complete one orbit in 11 h 15 min 44 s, minimum of 5 satellites are in view to users continuously, world-wide
- Cesium clocks on board satellites

GLONASS Signal Characteristics

- Each satellite transmits signal on unique frequency (FDMA)
    - Some satellites may use the same frequencies, but those satellites are placed in antipodal slots of orbit planes and they do not appear at the same time in a user’s view
- Two frequency bands
    - L1 = 1602 + n*0.5625 MHz
    - L2 = 1246 + n*0.4375 MHz
    - Where n is frequency channel number (n=0,1,2,…)
- Standard Precision (SP) Signal
    - PRN code clock rate 0.511 MHz
    - repeats each millisecond
    - civilian use
- High Precision (HP) Signal
    - PRN code clock rate 5.11 MHz
    - repeats each second
    - modulated by special code, includes anti-spoofing capability
    - military use

GLONASS Control System

- Several Command Tracking Stations (CTS) throughout Russia
  - St. Petersburg, Ternopol, Yeniseisk, Komsomolsk, Balkhash
  - track satellites in view and accumulate ranging data and telemetry from the satellite signals
  - transmit updated information to satellites, as well as other control information
  - ranging data is periodically calibrated using laser ranging devices at Quantum Optical Tracking Stations within GCS. Each satellite specially carries laser reflectors for this purpose.
- System Control Center (SCC) in Krasnoznamensk (Moscow region)
  - process CTS site information to determine satellite clock and orbit states and update the navigation message for each satellite.

GLONASS Control System (cont)

- **GLONASS system time-scale**
  - based on high-precision hydrogen clocks
  - relay signals to the phase control system (PCS) which monitors satellite clock time/phase as transmitted by the navigation signals and determines satellite corrections for upload
  - synchronized with UTC(SU)
  - also synchronized with UTC(CIS), which is maintained by the All Union Institute for Physical, Technical, and Radio-Technical Measurements (VNIIFTRI) in Mendeleevo, near Moscow
  - uses leap seconds
- **Ephemeris data in the Earth Parameter System 1990 (PZ-90), not GPS WGS-84**

Galileo

GALILEO

- Galileo is a joint initiative of the European Commission (EC) and the European Space Agency (ESA).
- It will be interoperable with GPS and GLONASS, the two operational global satellite navigation systems.
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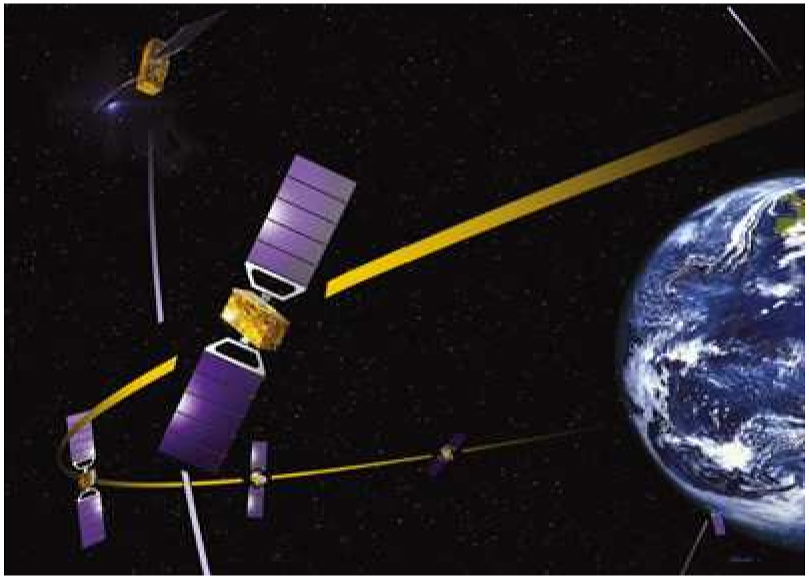
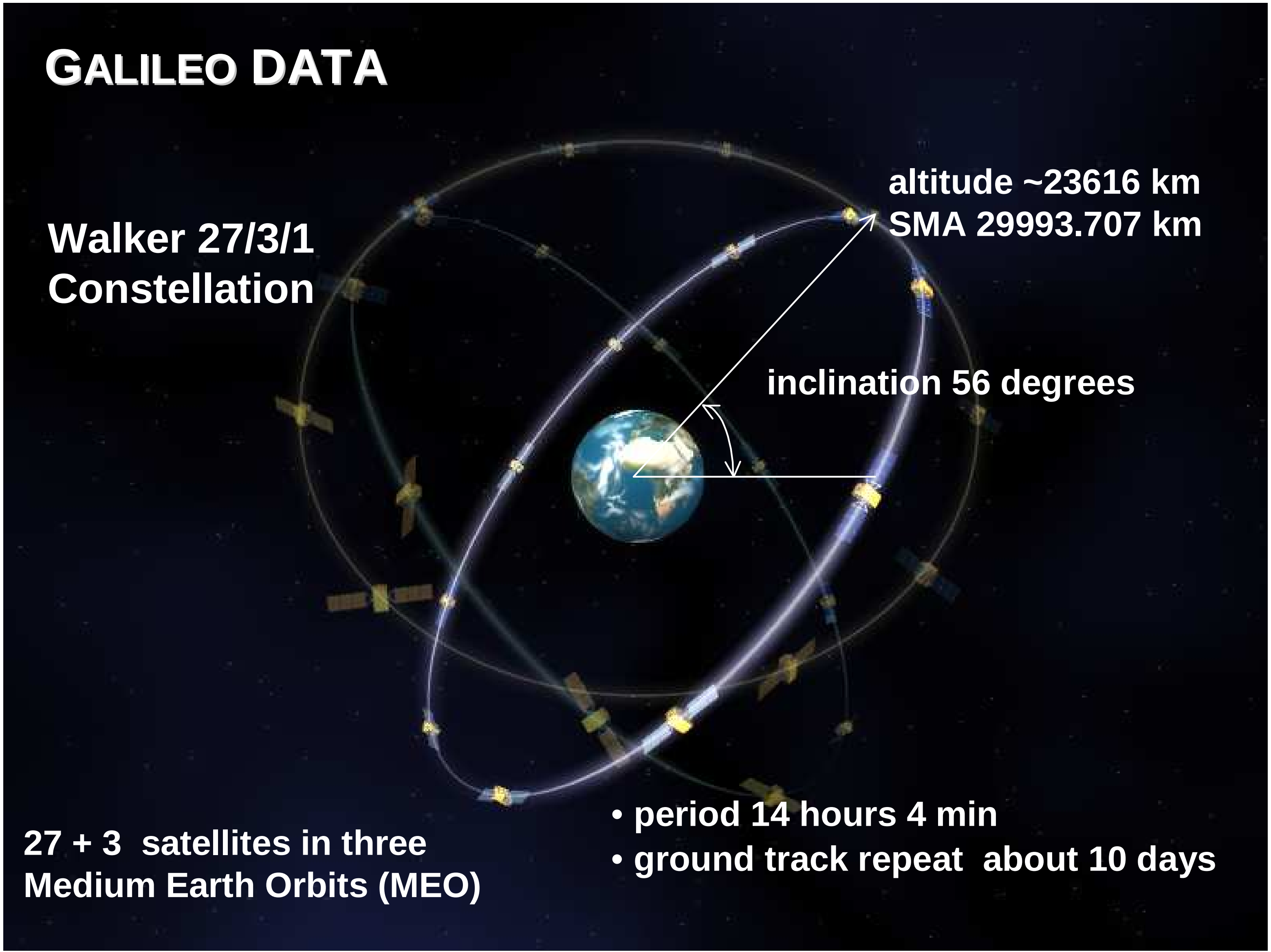


Galileo Constellation Configuration



GALILEO DATA

Walker 27/3/1
Constellation

altitude ~23616 km
SMA 29993.707 km

inclination 56 degrees

27 + 3 satellites in three
Medium Earth Orbits (MEO)

- period 14 hours 4 min
- ground track repeat about 10 days

The GALILEO Satellite Services

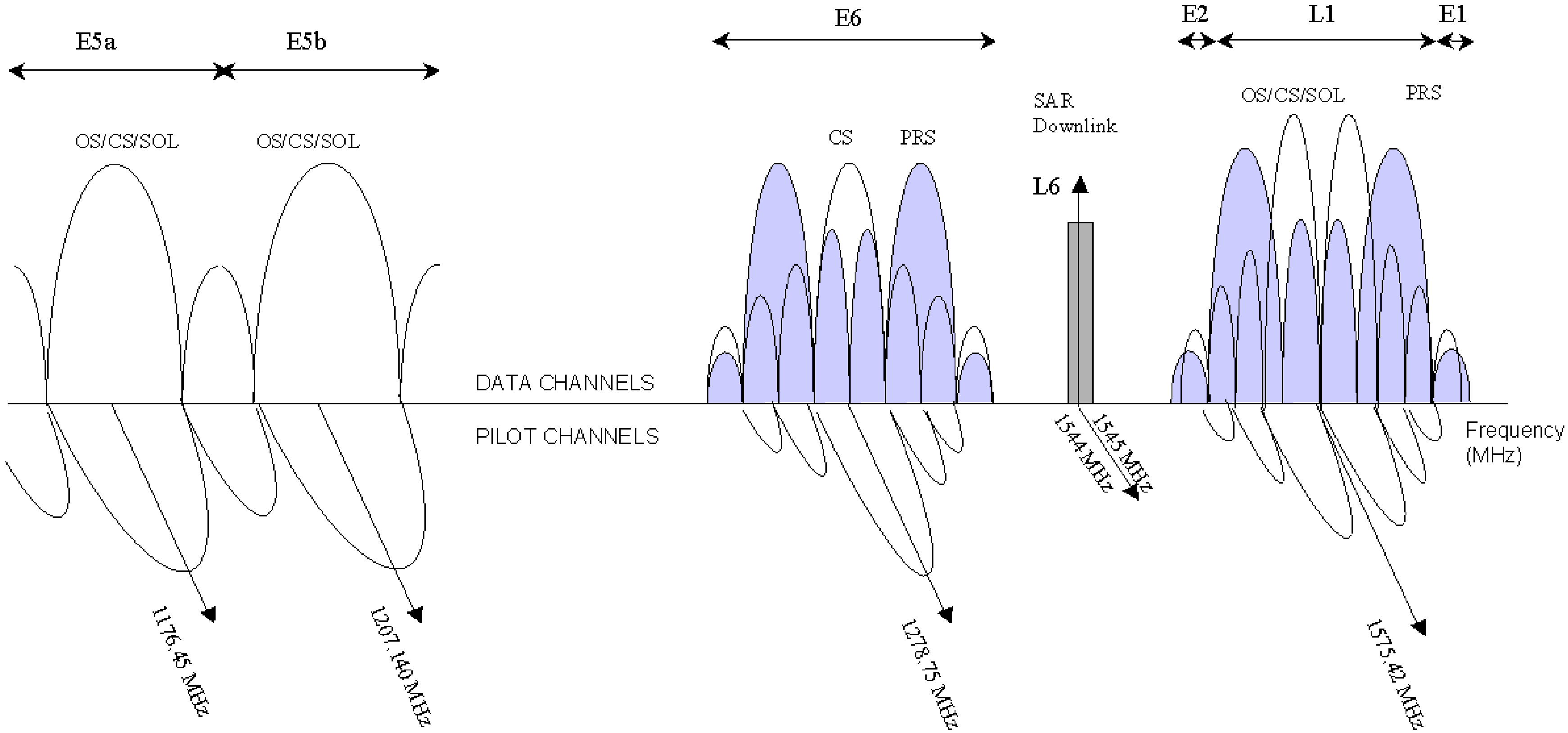
Position, Velocity and Time Services:

- **Open Service** - providing positioning, navigation and timing services, free of charge, for mass market navigation applications (future GPS SPS)
- **Commercial Service** - provides added value over the Open Service providing commercial revenue, such as dissemination of encrypted navigation related data (1 KBPS), ranging and timing for professional use - with service guarantees
- **Safety of Life Service** - Comparable with “Approach with Vertical Guidance” (APV-II) as defined in the ICAO Standards and Recommended practices (SARPs), and includes Integrity
- **Public Regulated Service** - for applications devoted to European/National security, regulated or critical applications and activities of strategic importance - Robust signal, under Member States control

Support to Search and Rescue

- Search and Rescue Service coordinated with COSPAS SARSAT

Galileo Navigation Signals and Frequencies

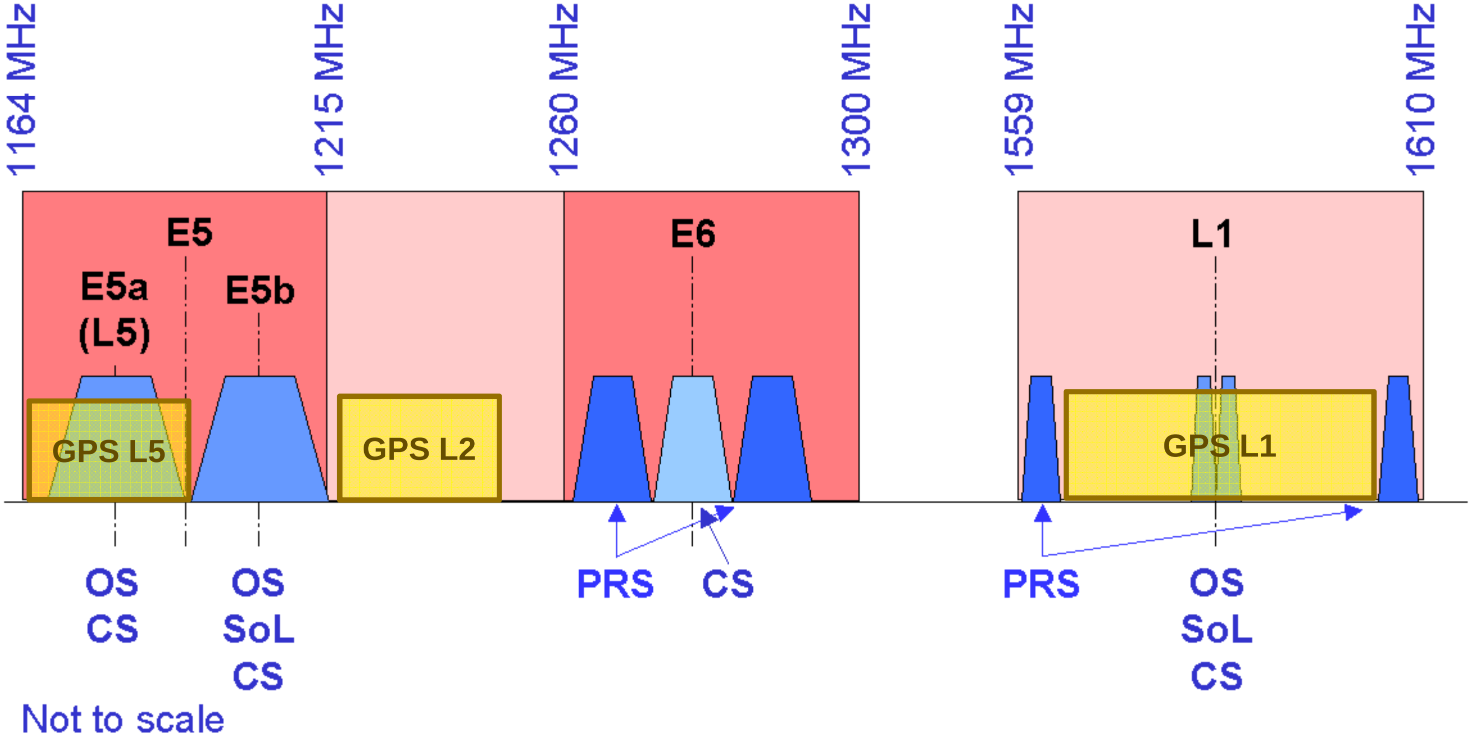

E5a
E5b
E6
E2
L1
E1
OS/CS/SOL
OS/CS/SOL
CS
PRS
SAR
Downlink
L6
OS/CS/SOL
PRS
DATA CHANNELS
PILOT CHANNELS
Frequency
(MHz)
1544 MHz
1545 MHz
1176.45 MHz
1207.140 MHz
1278.75 MHz
1575.42 MHz

Each Galileo Satellite will broadcast 10 navigation signals, making up the open (OS), safety-of-life (SOL), commercial (CS) and public regulated services (PRS)

http://www.esa.int/esaNA/SEM86CSMD6E_galileo_1.html

Galileo Navigation Signals and Frequencies

- **Galileo open services realized by using the signals at L1, E5a and E5b.**
- **Various configurations of dual and single frequency navigation use are possible.**
- **L1 and E5a Galileo signals interoperability with GPS**



1164 MHz
1215 MHz
1260 MHz
1300 MHz
1559 MHz
1610 MHz
E5
E5a
(L5)
E5b
E6
L1
GPS L5
GPS L2
GPS L1
OS
CS
OS
SoL
CS
PRS
CS
PRS
OS
SoL
CS
Not to scale

http://www.esa.int/esaNA/SEM86CSMD6E_galileo_1.html

Galileo System Design

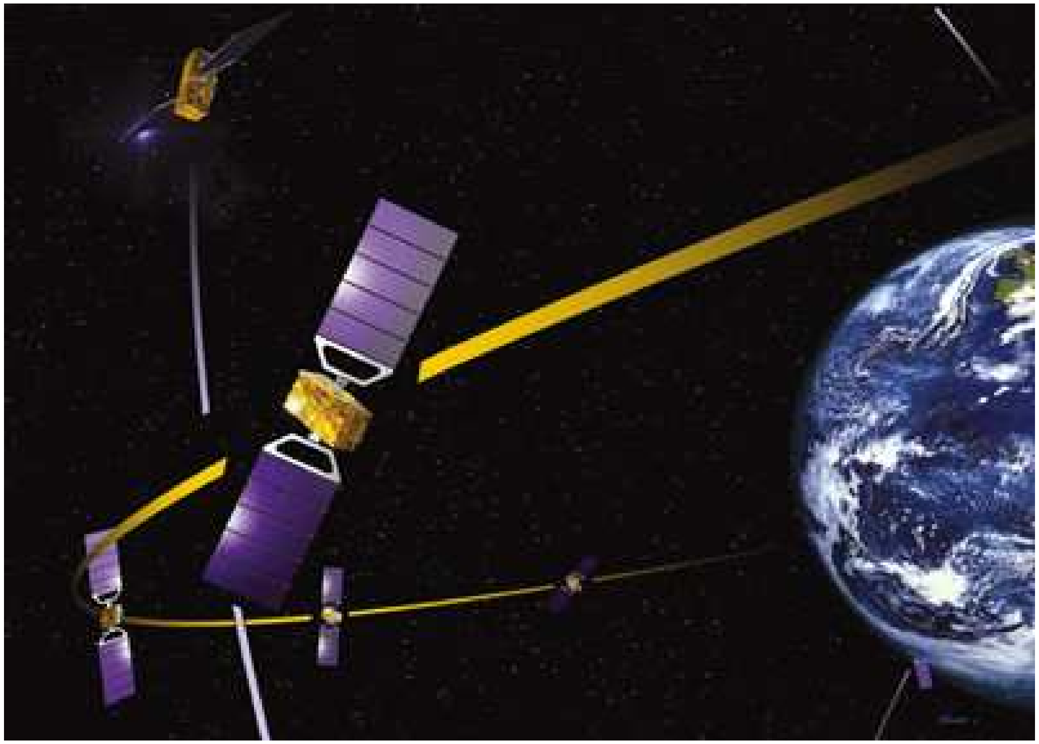
- Galileo Terrestrial Reference Frame (GTRF):
  - An independent realization of the International Terrestrial Reference System (ITRS) established by the Central Bureau of the International Earth Rotation Service (IERS).
  - Differences between WGS84 and GTRF ~ a few cm.
- Galileo System Time (GST):
  - Shall be a continuous coordinate time scale steered towards the International Atomic Time (TAI) with an offset of less then 33 ns.
  - Offset between GST and the GPS system time is monitored and broadcast to users, but may also be estimated in the receiver.
- Each Spacecraft will have 4 onboard clocks
  - 2 Rubidium Vapour
  - 2 Passive Hydrogen Maser

Agreement on GPS-Galileo Cooperation

- In 2004 the United States and the European Union established a partnership to ensure that GPS and Galileo will be interoperable at the user level for the benefit of civil users around the world.
  - Radio frequency compatibility and interoperability;
  - Trade and civil applications;
  - Design and development of the next generation of systems; and
  - Security issues related to GPS and Galileo.
- The agreement:
  - Ensures that Galileo's signals will not harm the navigation warfare capabilities of the United States and the North Atlantic Treaty Organization military forces
  - Calls for non-discrimination and open markets in terms of trade in civil satellite navigation-related goods and services
  - Includes an agreement to establish a common civil signal at the L1 frequency
- Additional availability, precision, and robustness provided by complementary systems

GALILEO References

- Further information can be found here:
  - http://www.esa.int/esaNA/index.html



BeiDou / Compass

Chinese Compass System

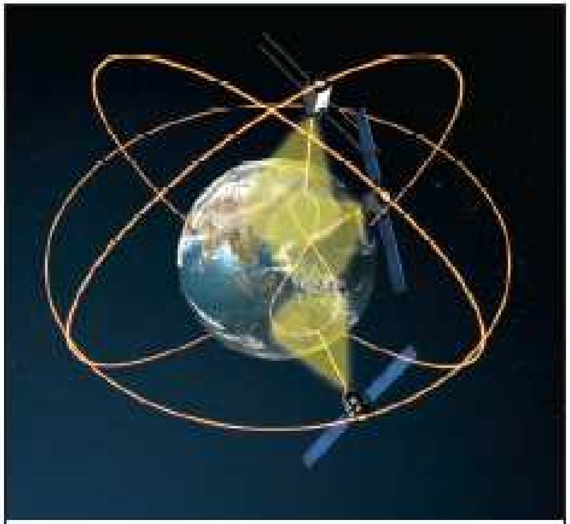
- In 2006 China announced plans to develop a 35-satellite, global navigation system
- The **Compass** system (also known as **BeiDou**) will include 5 geostationary orbit (GEO) satellites and 30 medium Earth orbit (MEO) satellites
- BeiDou will provide three carrier frequencies foreseen to be interoperable with other systems.
- Demonstration Phase – completed in 2003 with launch of 3 Geostationary satellites
- Second Phase – provision of satellite navigation services for Asia-Pacific region – achieved by 2012
  - Currently four MEO (21,500 km orbit) satellites on orbit:
    - First MEO satellite launch 2007
    - Latest launch 17 Jan 2010

http://www.beidou.gov.cn/

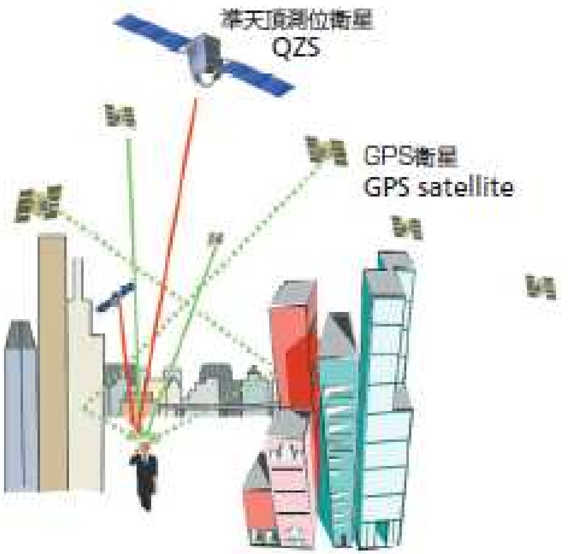
Quasi-Zenith Satellite System (QZSS)

Japanese Quasi-Zenith Satellite System (QZSS)

- QZSS is a GPS augmentation system serving Japan and the Asia-Pacific region.
- Consists of three (3) satellites in highly-inclined, geostationary orbits so that one satellite always appears near the zenith above the region of Japan.



準天頂衛星システムの構成
Quasi-Zenith Satellite System



準天頂衛星システムの利点

準天頂測位衛星3機のうちの1機の仰角は東京で常時70度以上、日本中どこでも60度以上です。ビルの谷間でも測位可能な時間を増やすとともに、反射波の影響の少ない信号を届けることができます。

Advantage of Quasi-Zenith Satellite System

The one of the three Quasi-Zenith Satellites elevation angle exceeds 70 degrees over Tokyo, and is more than 60 degrees throughout Japan.

The signals from a QZS, which is less error due to multipath and reflection, reach users in urban canyon and enhance GPS availability.

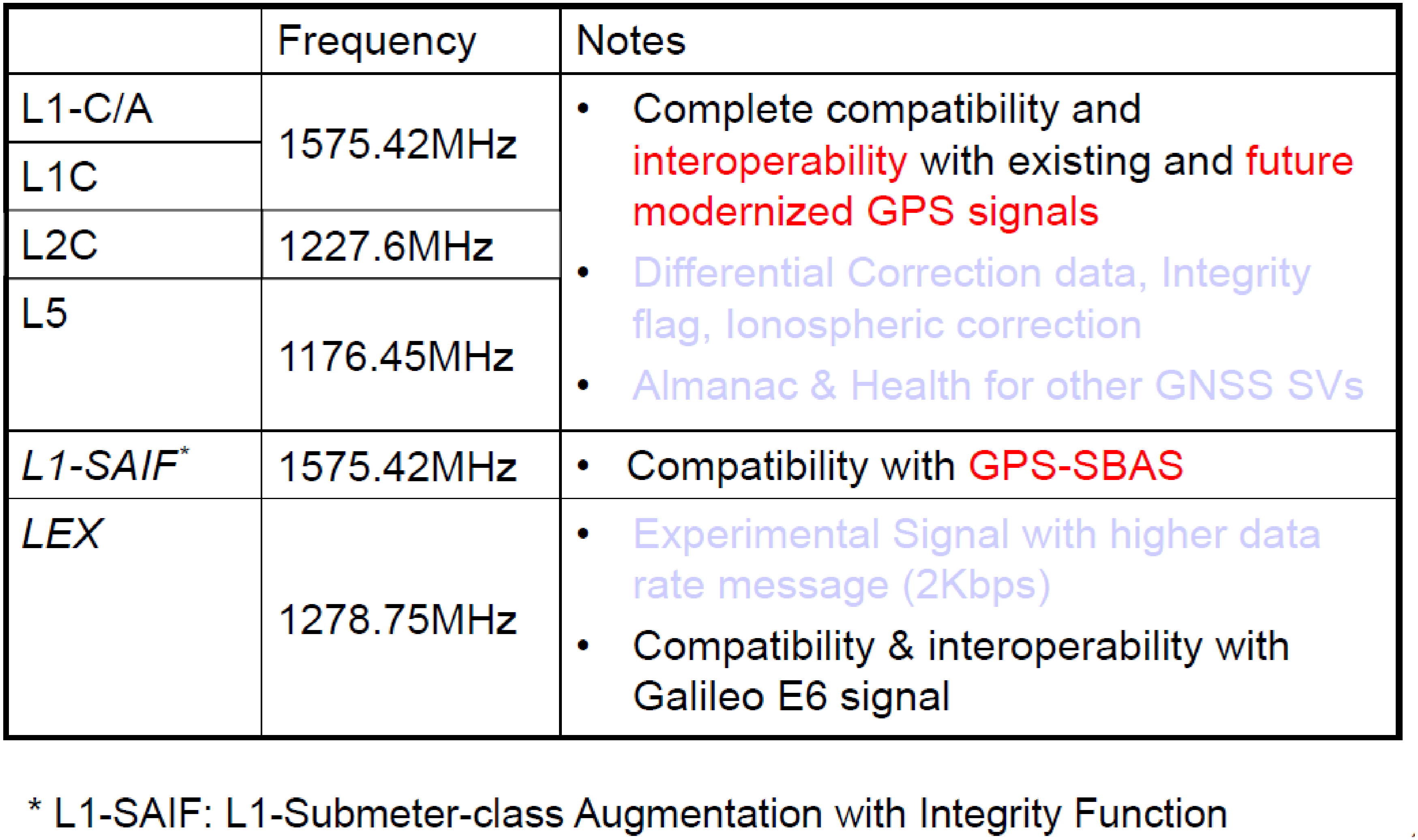
http://www.jaxa.jp/pr/brochure/pdf/04/sat12.pdf

QZSS - Continued

- GPS Availability Enhancement
  - Improves availability of satellite positioning for areas such as urban canyon and mountain terrain
  - The usage of the QZS at high elevation angles in combination with GPS,
- GPS Performance Enhancement
  - Achieves high accuracy by transmitting position correction data
  - Achieves high reliability by sending integrity data
- Based on 2006 agreement between the U.S. and Japan, the navigation signals and messages of the QZSS offer complete interoperability with those of GPS
- First QZSS satellite (QZS-1) launched in Sept, 2010
  - Utilization demonstration during 2011

http://qzss.jaxa.jp/is-qzss/index_e.html

QZSS Planned Signals



	Frequency	Notes
L1-C/A	1575.42MHz	• Complete compatibility and interoperability with existing and future modernized GPS signals • Differential Correction data, Integrity flag, Ionospheric correction • Almanac & Health for other GNSS SVs
L1C		
L2C	1227.6MHz	
L5	1176.45MHz	
*L1-SAIF**	1575.42MHz	• Compatibility with GPS-SBAS
LEX	1278.75MHz	• Experimental Signal with higher data rate message (2Kbps) • Compatibility & interoperability with Galileo E6 signal

* L1-SAIF: L1-Submeter-class Augmentation with Integrity Function

http://www.navcen.uscg.gov/pdf/cgsicMeetings/50/%5B2%5DJAPAN_REPORT_50TH_CGSIC10_9.pdf

Indian Regional Navigational Satellite System (IRNSS)

- Autonomous regional satellite navigation system being developed by Indian Space Research Organization .
- The proposed system would consist of a constellation of seven satellites and a support ground segment.
  - ❑ Three satellites in Geostationary orbits
  - ❑ Remaining satellites in highly elliptical orbits
- First launch targeted for 2011
- Completed and operational by 2014

http://www.oosa.unvienna.org/pdf/icg/2008/expert/2-3.pdf http://www.irnssindia.com/

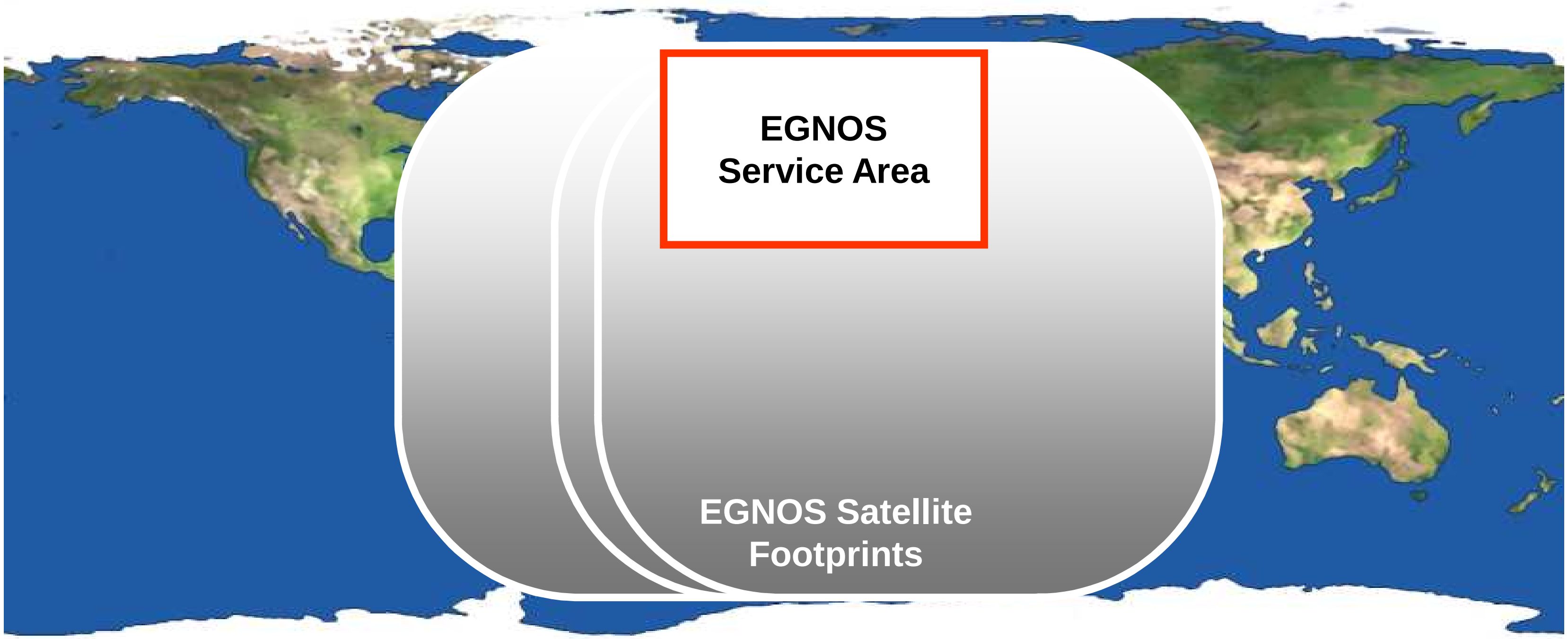
Indian GPS Aided Geo Augmented Navigation (GAGAN)

- GAGAN is a Satellite Based Augmentation System (SBAS) over the Indian Air-space primarily meant for civil aviation
- Jointly implemented by the Indian Space Research Organization (ISRO) and the Airports Authority of India (AAI)
- Two signals: L1 and L5
- Technology Demonstration Phase completed in 2007
- Operational phase of GAGAN expected to be completed by 2011

http://www.oosa.unvienna.org/pdf/icg/2008/expert/2-3.pdf

EGNOS

- The European Geostationary Navigation Overlay Service (EGNOS) augments the US GPS satellite navigation system and makes it suitable for safety critical applications such as flying aircraft or navigating ships through narrow channels.


EGNOS
Service Area
EGNOS Satellite
Footprints

http://www.esa.int/esaNA/GGG63950NDC_egnos_0.html

EGNOS Continued

- Consists of three geostationary satellites and a network of ground stations
- EGNOS is a joint project of ESA, the European Commission and Eurocontrol, the European Organisation for the Safety of Air Navigation.
- The EGNOS Open Service has been available since 1 October 2009.
- EGNOS positioning data are freely available in Europe through satellite signals to anyone equipped with an EGNOS-enabled GPS receiver.

MTSAT Space-based Augmentation System (MSAS)

- Japanese SBAS (Satellite Based Augmentation System)
- Supports differential GPS (DGPS) designed to supplement the GPS system by reporting (then improving) on the reliability and accuracy of those signals
- MSAS for aviation use was commissioned on September 27, 2007

System of Differential Corrections and Monitoring (SDCM)

- SBAS counterpart to the WAAS and the EGNOS covering the Russian Federation.
- The SDCM would perform integrity monitoring of both GPS and GLONASS satellites as well as provide differential corrections and a posteriori analyses of GLONASS system performance.
- Network of ground reference stations and geostationary satellites
- Will launch three geostationary satellites in the 2010-2013 timeframe, the first scheduled to be operational in 2011