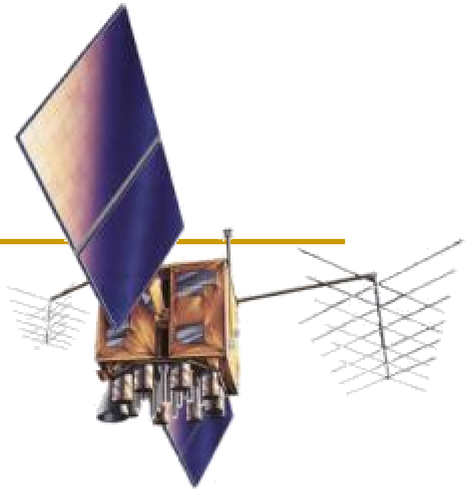
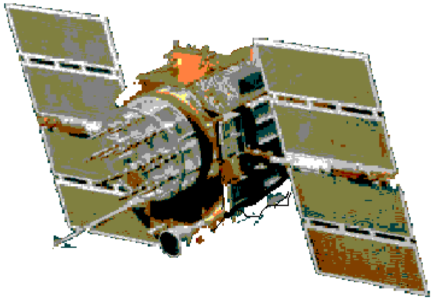


Introduction to GPS and other Global Navigation Satellite Systems

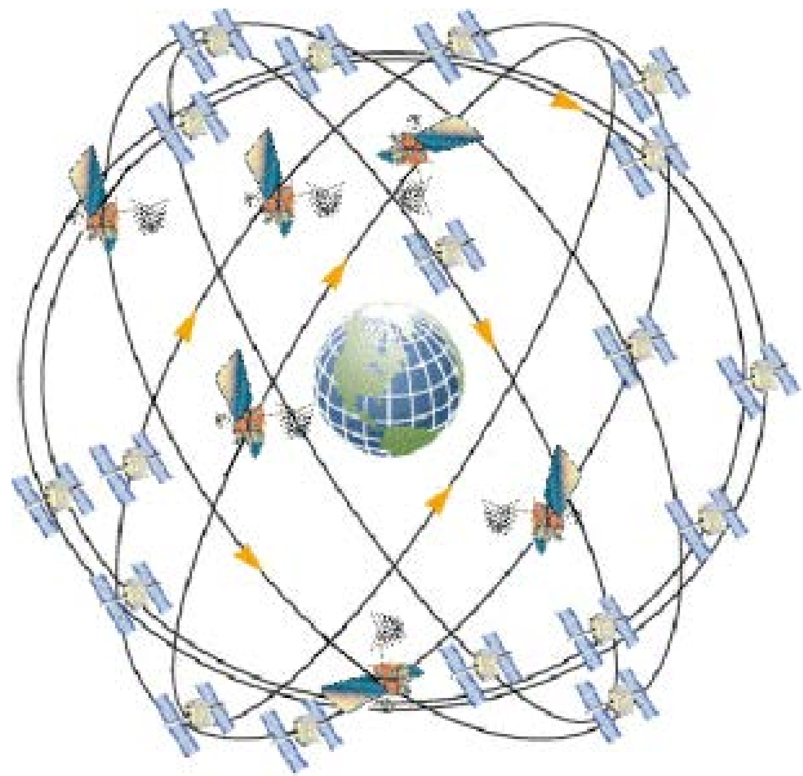
Luke Winternitz
NASA/Goddard Space Flight Center Code 596
(Acknowledgment to Mike Moreau NASA/GSFC Code 595)



42nd Annual Time and Frequency Metrology Seminar
8 June 2017

Outline

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



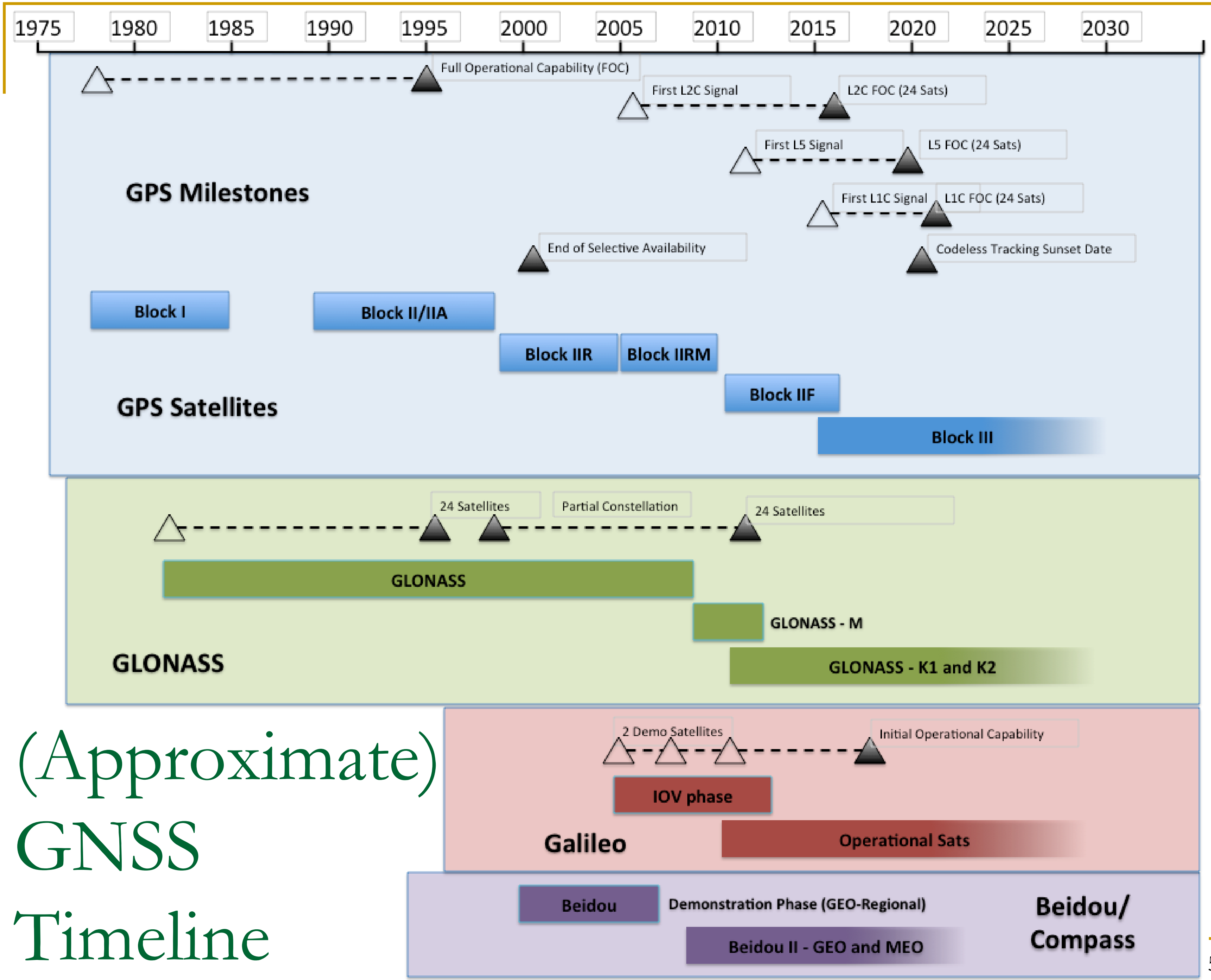
Applications of Satellite Navigation are Everywhere…

- Military
- Civilian
  - Transportation
  - Public services
  - Precise machine control
  - Timing and frequency
  - Surveying
  - Surveillance
  - Recreational
  - Space
  - Scientific applications
- US spends annually about $1.0B-1.5B on GPS
- Annual direct economic benefit has been estimated at about $70B, 0.4% GDP*

www.gps.gov/governance/advisory/meetings/2015-06/leveson.pdf

Satellite Navigation Systems Provide:

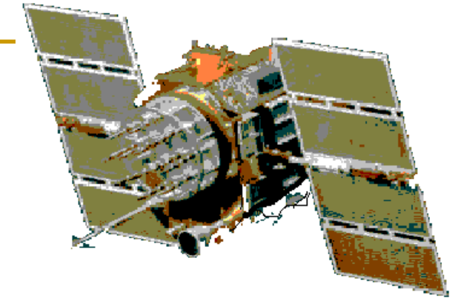
- Accuracy
  - three dimensional accuracies of a few meters, and down to the level of millimeters for users with specialized equipment/processing
- Availability
  - signal available anywhere on Earth where the user has a clear view of the sky
- Integrity
  - the assurance that the expected performance will be realized



(Approximate) GNSS Timeline

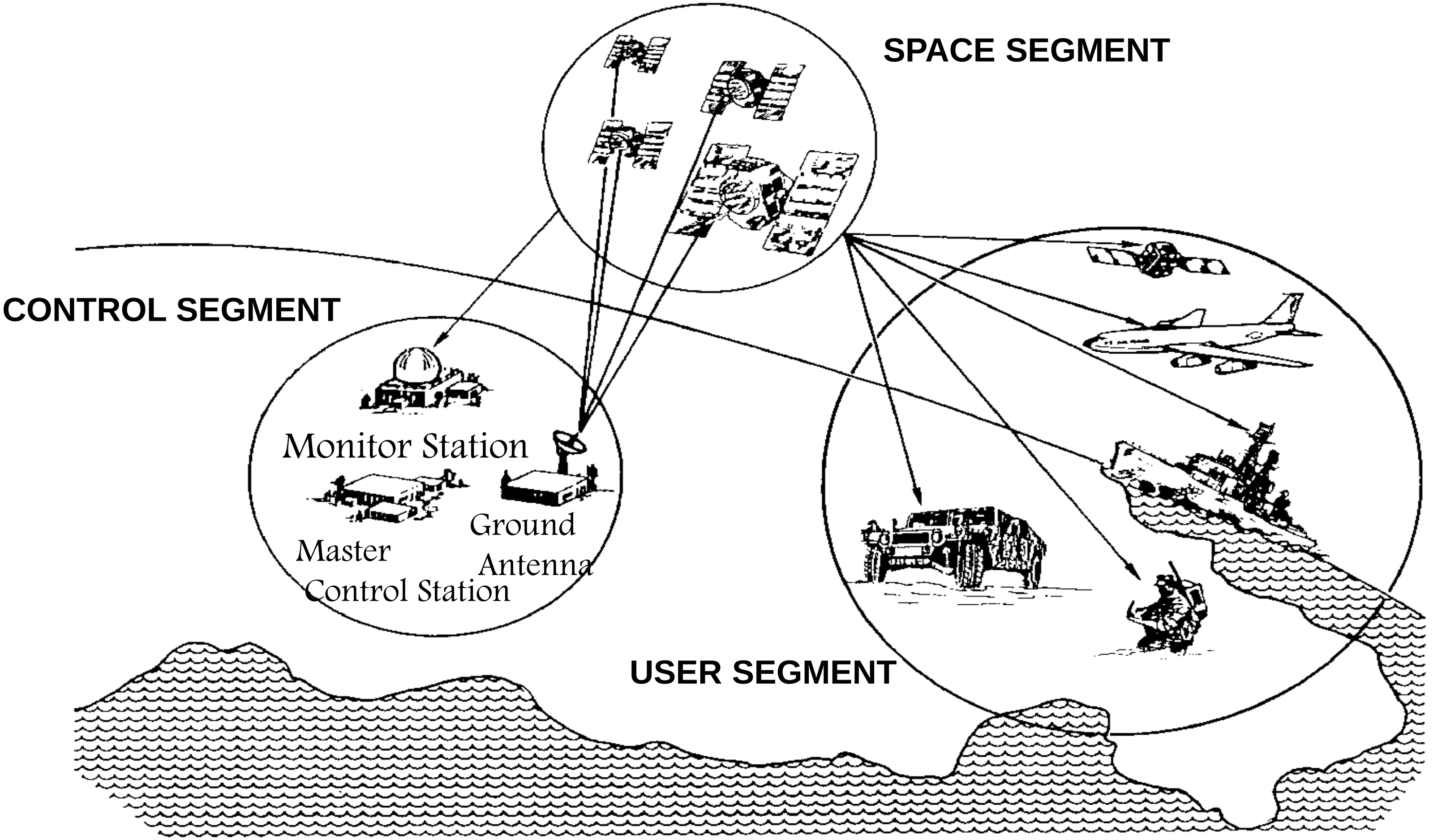
The U.S. Global Positioning System (GPS) - History, Status, and Future

GPS History

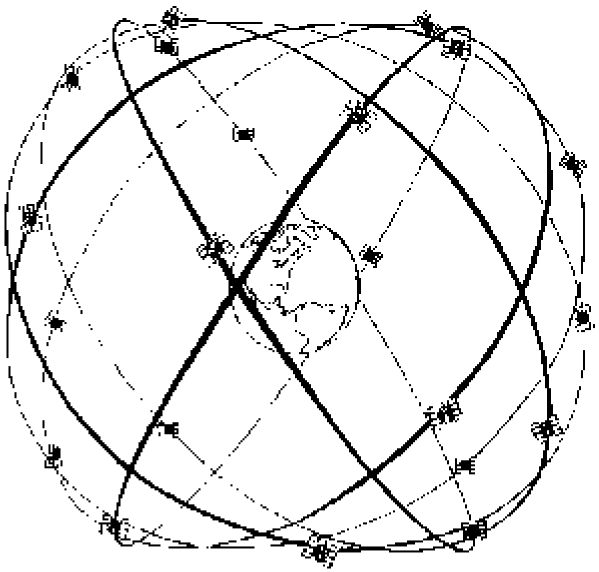


- Developed by the US Department of Defense
  - Early GPS program driver was Trident Missile Program (Submarine launched ICBM)
  - Satellites carry a nuclear detonation detection payload
- Early Satellite Navigation Systems
  - TRANSIT (Doppler positioning)
  - Timation (first atomic frequency standards 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



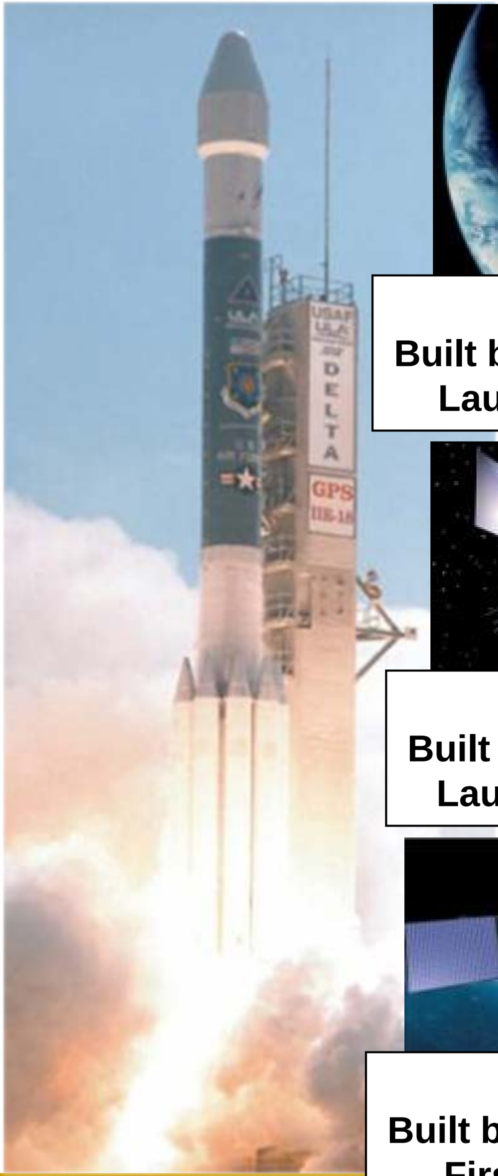
GPS Space Segment



- 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
- There have been 1-4 replenishment launches per year in recent years

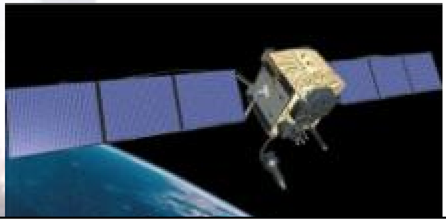
Current GPS Constellation Status

- 31 space vehicles currently in operation (2016 status in parentheses)
  - 0 (0) GPS IIA
  - 12 (12) GPS IIR
  - 7 (7) GPS IIR-M
  - 12 (12) IIF
- several additional satellites in residual status
- 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

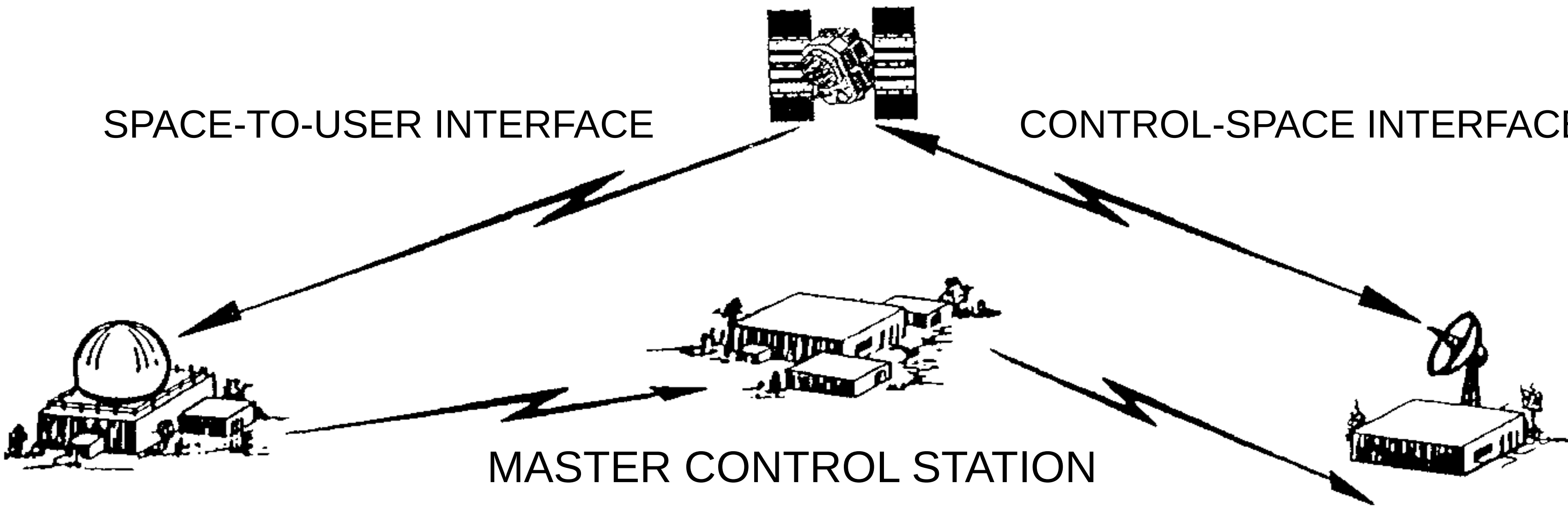


Block IIF
Built by Boeing Aerospace
First Launch in 2010

GPS Control Segment

SPACE VEHICLE

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



MONITOR STATION

- Sends raw observations to MCS

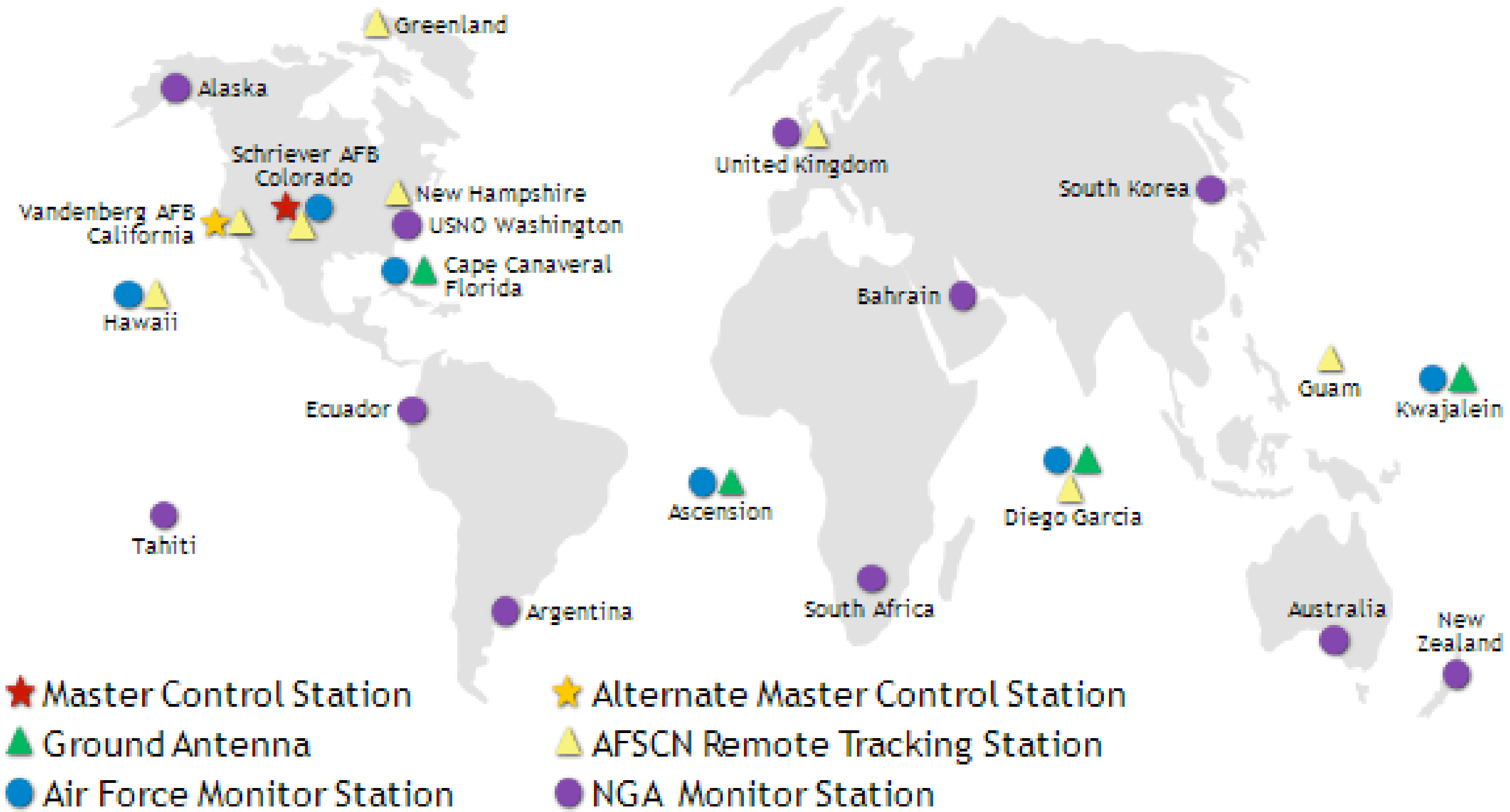
MASTER CONTROL STATION

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

GROUND ANTENNA

- Sends new upload to SV

Control Segment – Map



- The current operational control segment includes a master control station, an alternate master control station, 12 command and control antennas, and 16 monitoring sites.
- Data from Air Force and NGA monitor stations incorporated into Control Segment Kalman filter solution.

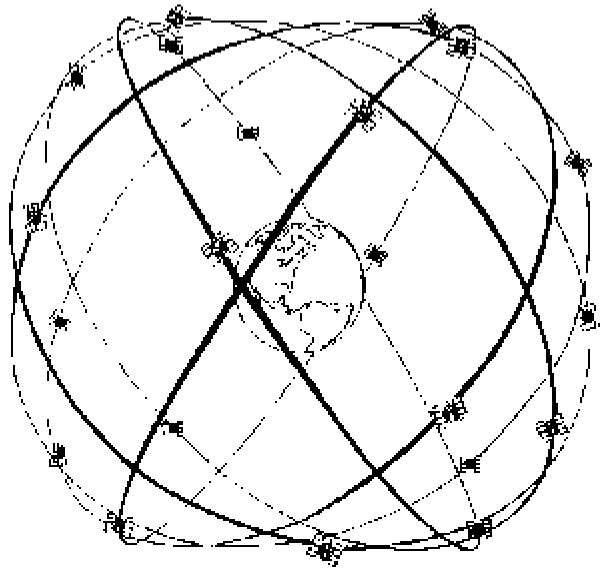
GPS User Segment

- 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 encrypted military codes transmitted on L1 and L2 signals.
- High performance civil receivers use special codeless or semi-codeless techniques to track the legacy military signals, and now track new signals provided by GPS and other GNSS systems.

Military Spacecraft (~$2,000,000)

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
    - Available only to *authorized* (military) users on both L1 and L2 carriers
    - 267 day repeat interval, divided into week-long segments transmitted by each satellite
- **PRN Codes are 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
  - Robustness against interference
  - Improved indoor, mobile, and urban use
  - Interoperability with other GNSS constellations
  - Backward compatibility

- Achieved through
  - Modernized Space and Ground segments
  - New signals
  - Improved “CNAV” data message

GPS IIF Status

- The Air Force launched GPS IIF-12 on 5 Feb 2016
  - IIFs L1C/A, L2C, L5 + military signal capable
  - Providing enhanced GPS clock performance
- All 12 total GPS IIFs on orbit
  - Best accuracies in constellation
  - Demonstrated Flex Power capability

Image: ULA, http://www.schriever.af.mil/news/story.asp?id=123468589

Image: NASA/Boeing

GPS III Status

- Newest block of GPS satellites
  - First to broadcast common L1C signal
  - Multiple civil and military signals;
    - L1 C/A, L1 P(Y), L1M, L1C,
    - L2C, L2 P(Y), L2M,
    - L5
  - Three Rubidium clocks
  - First launch in ~2018 timeframe
- Lockheed Martin in Denver CO awarded contract for two (SV01/02) development and six operational satellites (SV03-08), with option for two more (SV09-10) exercised in 2016.
- GPS III SV11+ is an open procurement; awards expected in 2018. Will add:
  - Laser Retro-reflector Array
  - Search and Rescue payload

http://gpsworld.com/2016-in-review-gps-navigates-the-future/

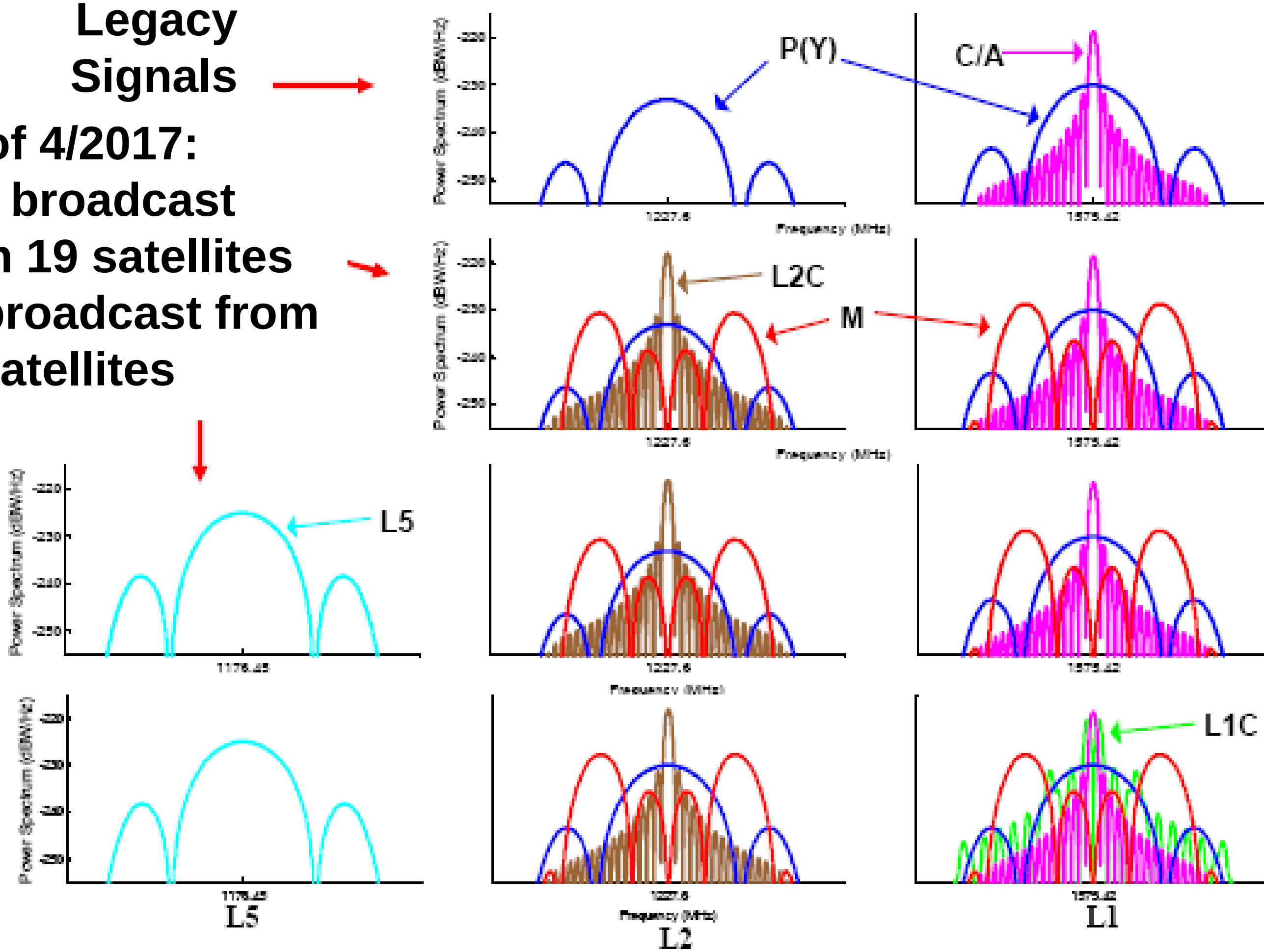
GPS Modernization- new civil signals

- L2C (1227.60 MHz= 120*10.23 MHz)
  - Allows ionospheric error removal
  - Two time-multiplexed PRN codes, one is dataless
  - 1st launch: Sep 2005 (GPS IIR-M)
- L5 (1176.45MHz = 115*10.23 MHz)
  - Designed for safety of life applications
  - In highly protected ARNS band
  - First transmitted by GPS Block IIF (demo payload on SV49)
- L1C (1575.42 MHz = 154*10.23 MHz)
  - Interoperable with other GNSS systems
  - Multiplexed Binary Offset Carrier modulation reduces interference with L1C/A, may allow higher accuracy tracking
  - First transmitted by GPSIII
- All modulated with improved CNAV or CNAV-2 packetized data message with forward error coding.
  - First demonstration conducted in Jun 2013.
  - Pre-operational CNAV now continuously broadcast with daily updates.

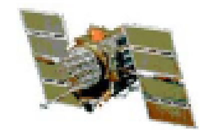
GPS Modernization – Spectrum

Legacy Signals

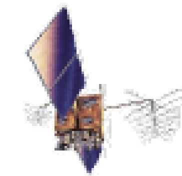
As of 4/2017:
L2C broadcast from 19 satellites
L5 broadcast from 12 satellites



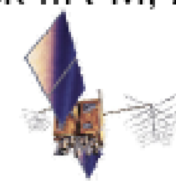
Block IIA 1990



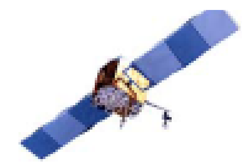
Block IIR 1997



Block IIR-M, 2005



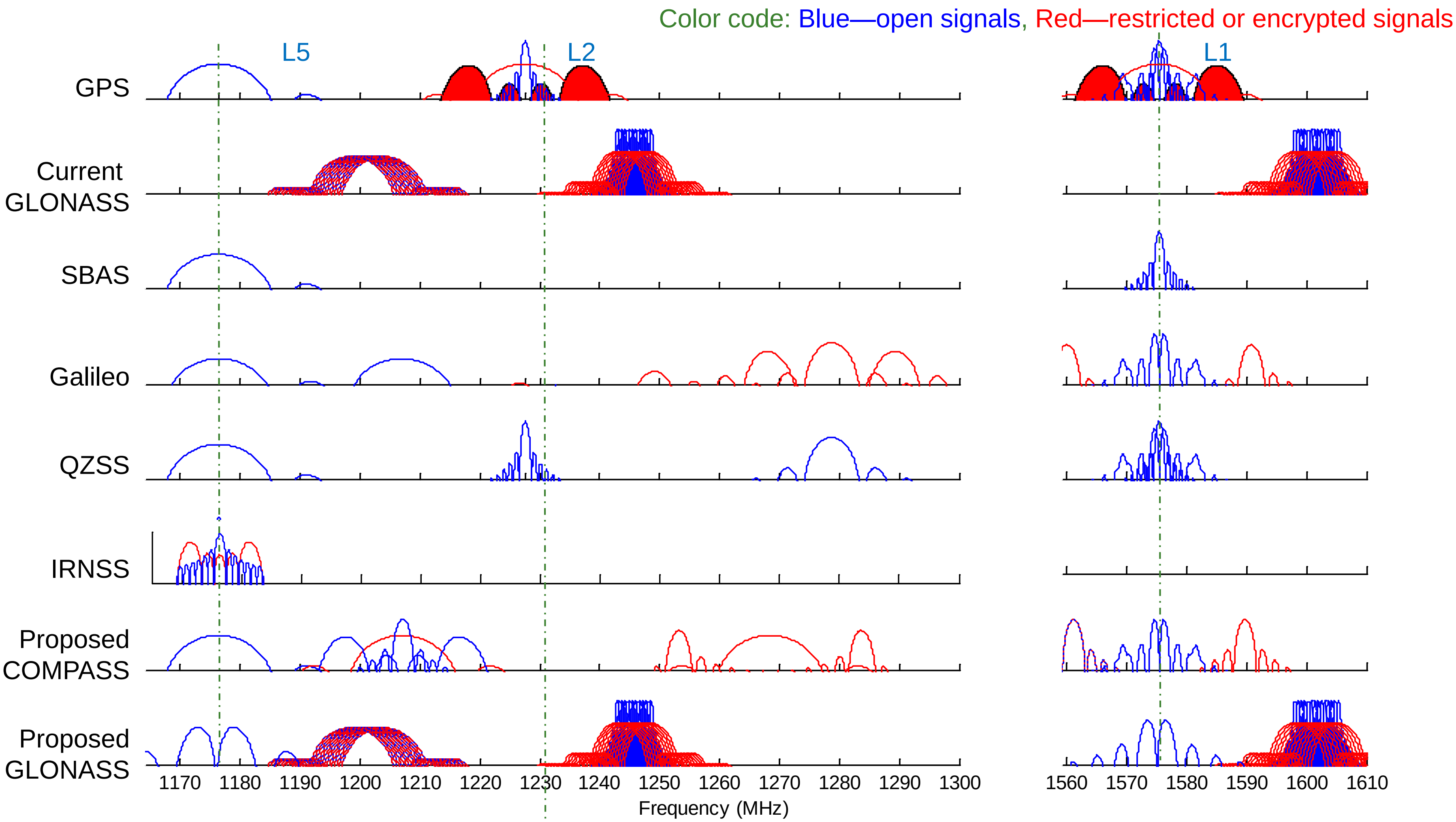
Block IIF, 2010



Block III, 2017

ARNS Band ***RNSS Band*** ***ARNS Band***

Spectrum of Other GNSS Systems

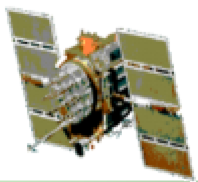
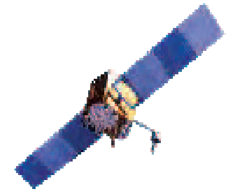


GPS Modernization – Ground

- Legacy Accuracy Improvement Initiative (L-AII, completed 2008)
  - Added 10 NGA monitoring sites to bring total to 16
- Architecture Evolution Plan (AEP, 2007-current)
  - Modern IT system, updated monitoring stations and ground antennas. Manages current modernized constellation
- Launch and early orbit, Anomaly resolution, and Disposal Operations (LADO, fielded 2007)
  - Handles GPS satellites outside operational constellation
- Next Generation Operational Control Segment (OCX, contract awarded 2008) will eventually replace OCS, control GPS III
  - Multiphase rollout 2017-2021
- OCS Contingency Ops program (delivery in 2019) will allows management of GPS III's "IIF features" of nav payload prior to OCX Block 1 (2021)

www.gps.gov, http://gpsworld.com/2016-in-review-gps-navigates-the-future/

GPS Modernization Summary

	1995	2005	2010	2017 - 2025
	GPS IIA/GPS IIR	**GPS IIR-M**	**GPS IIF**	**GPS III**
Space Segment				
	• Standard Positioning Service (SPS) o Single frequency (L1 C/A) coarse acquisition code navigation • Precise Positioning Service (PPS) o Y-Code (L1 P(Y) & L2 P(Y))	• IIA/IIR capabilities plus: o 2nd civil signal (L2C) o M-Code (L1M & L2M)	• IIR-M capability plus o 3rd civil signal (L5) o 12 year design life	• Backward compatible • 4th civil signal (L1C) • Increased accuracy • Increased integrity • Increased design life

Ground Control Segment	**Legacy Control System**	**Architecture Evolution Plan (AEP)/ OCS COops**	**Next Gen Control Seg. (OCX)**

Courtesy Thomas D. Powell, GPS Systems Engineering, The Aerospace Corporation, 18 April 2010 (with small updates)

GPS Documentation

- System technical docs available on www.gps.gov
- GPS IS-200:
  - Spec. of legacy C/A & P codes and NAV message
  - Rev E and beyond adds L2C and CNAV
- GPS IS-800:
  - Specification of L5, and L5 CNAV

- SPS & PPS Performance standards
  - Defines the guaranteed level of performance in terms of Signal in Space (SIS) accuracy and Constellation design
  - Current system performance surpasses minimum spec and is improving.

Satellite Navigation System Fundamentals

Importance of Precise Timing to GPS

- Precise timing is fundamental to realizing high performance from satellite navigation systems
- 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 / speed of light = 3.3×10^{-9} s
- GPS control segment predicts GPS clock performance over a 12 hour period (nominal frequency at which clock data is uploaded to the GPS satellites)
  - 3.3 ns of 12 hours 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 synchronized to *GPS time* which is coarsely 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, but in practice much closer.
- Traceability to UTC(USNO) enables precise time and frequency transfer on a global scale.

Modeling of Relativistic Effects in GPS

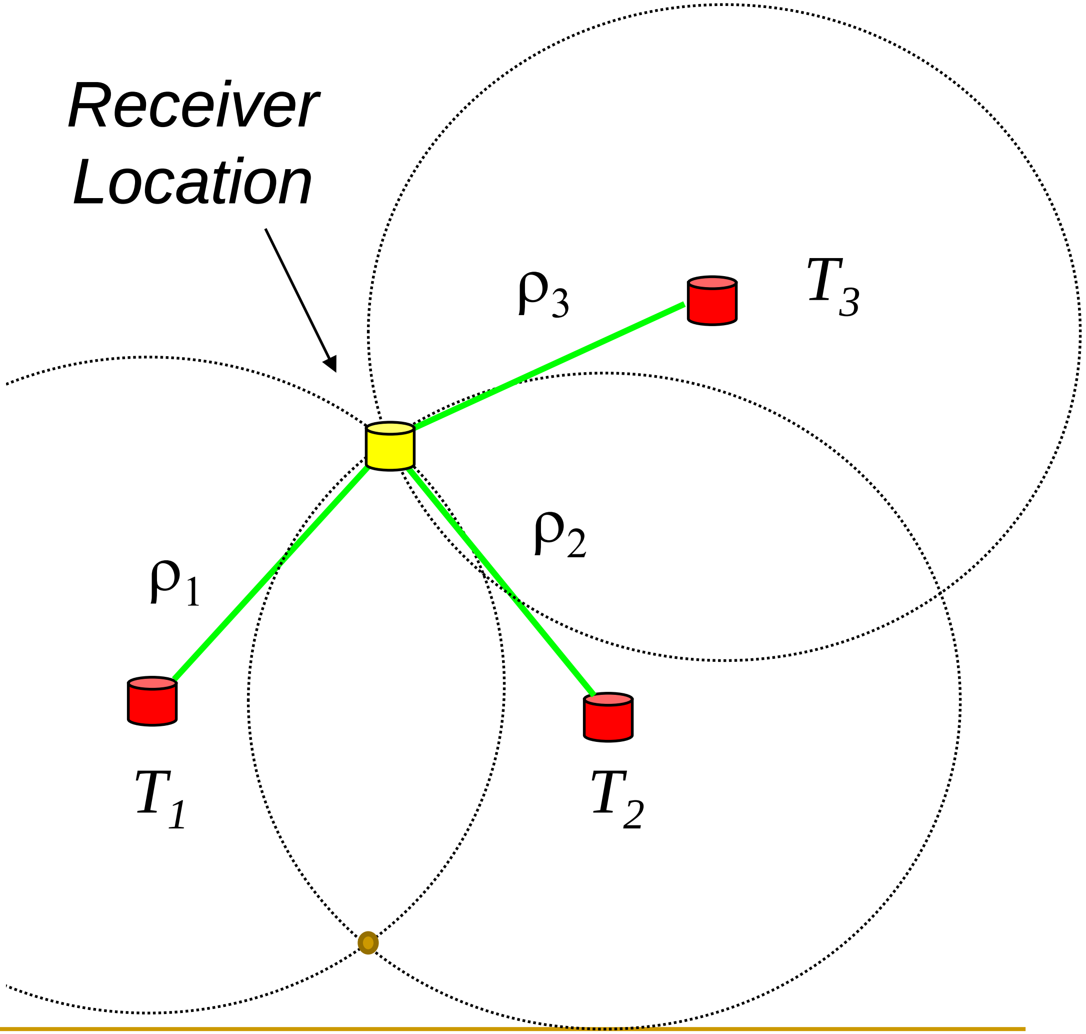
- Atomic clocks in GPS satellites are given a fixed fractional frequency offset of -4.46475×10^{-10} to compensate for relativistic effects in the GPS satellite orbits
    - Second-order Doppler shift – a clock moving in an inertial frame runs slower than a clock at rest
    - Gravitational frequency 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 Basic Principles

- Satellite navigation is based on:
  - Precise synchronization of radio beacons
  - The constancy of the speed of light connecting signal transit-time to range regardless of relative motion
- GPS and other systems use the concept of multi-lateration for position/time solution:
  - Satellite transmitter positions are known
  - Receiver position is unknown
- Measured transit-time of signals constrains receiver position relative to transmitters

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 is made using ranging code on the signal*



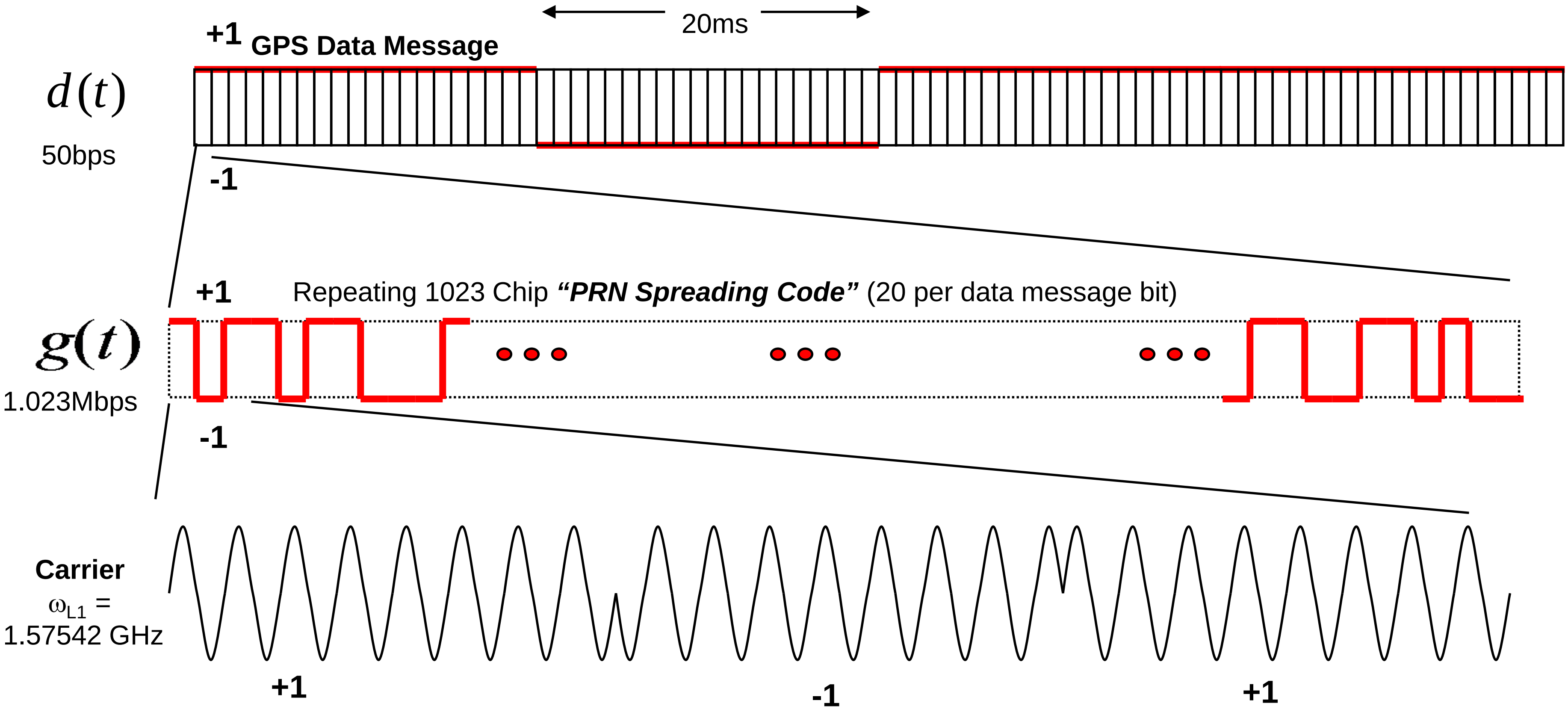
Position Solution

- 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 (in WGS84 coord frame)
    - corrections for errors in the sat. clock (relative to GPStime)

Legacy GPS signal design

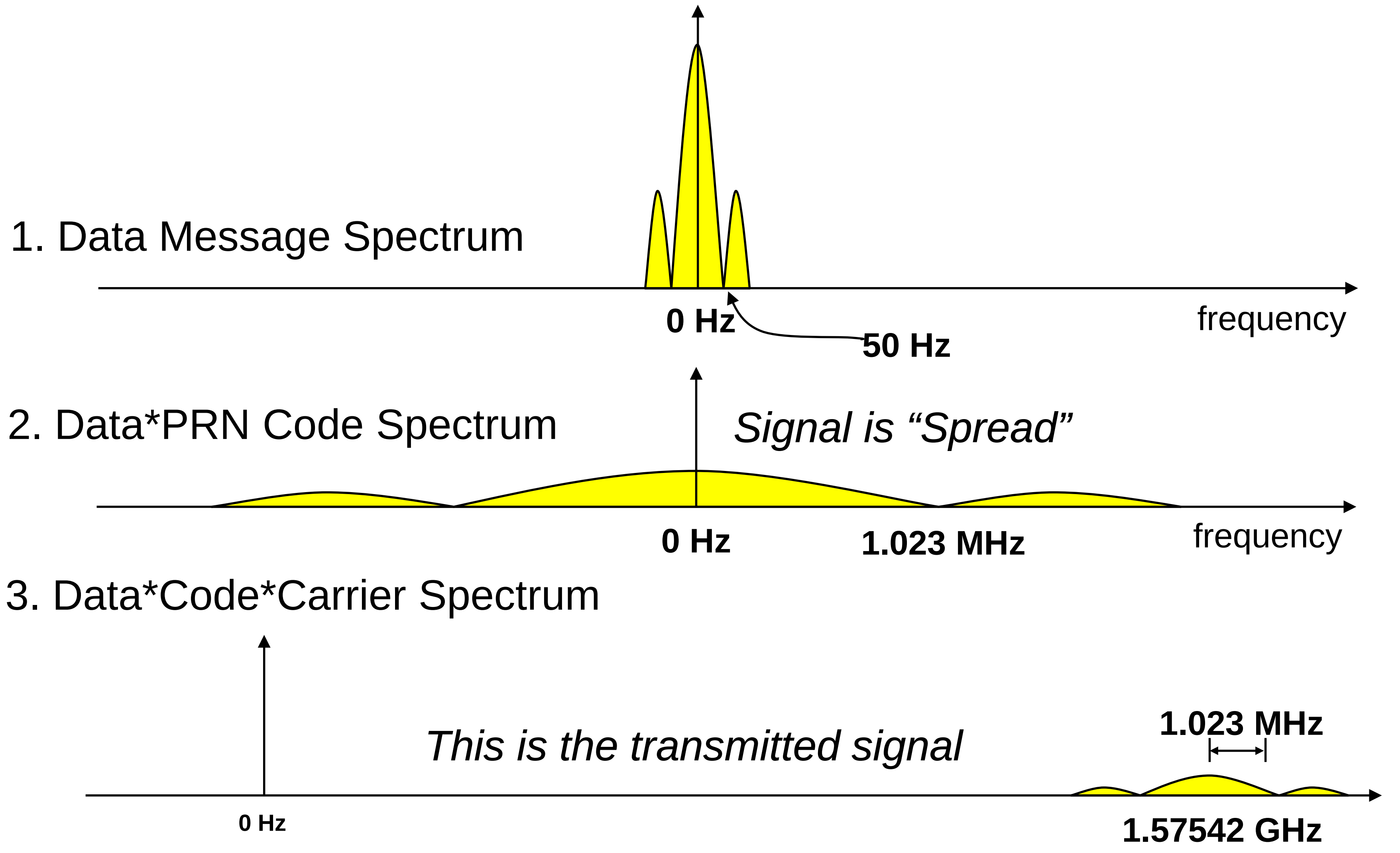
- L-band spread-spectrum digital communication system using binary phase shift keying (BPSK) to modulate carrier with Pseudo-Random Noise (PRN) code and low-rate data
- Each transmitter uses unique PRN sequence enabling
  - Transmission in common freq. band: Code-Division Multiple Access (CDMA)
  - Precise synchronization of received signals: the basis of ranging
- 37500 bit 50Hz binary data message
  - High accuracy orbits & clocks for individual satellite every 30s
  - Lower accuracy orbits and clocks for whole constellation in 12.5min
  - Constellation health, UTC correlation data, etc.
- Same principles apply to modernized signals

GPS L1 C/A Signal (Time Domain)



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

GPS L1 C/A Signal (Frequency Domain)



GPS signal channel effects

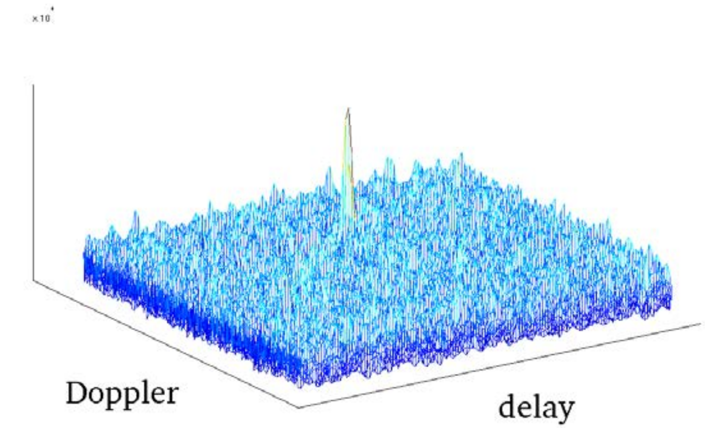
- The signal collected by the receiver is attenuated and delayed version of transmission. Noise from radio background and receiver components add in.

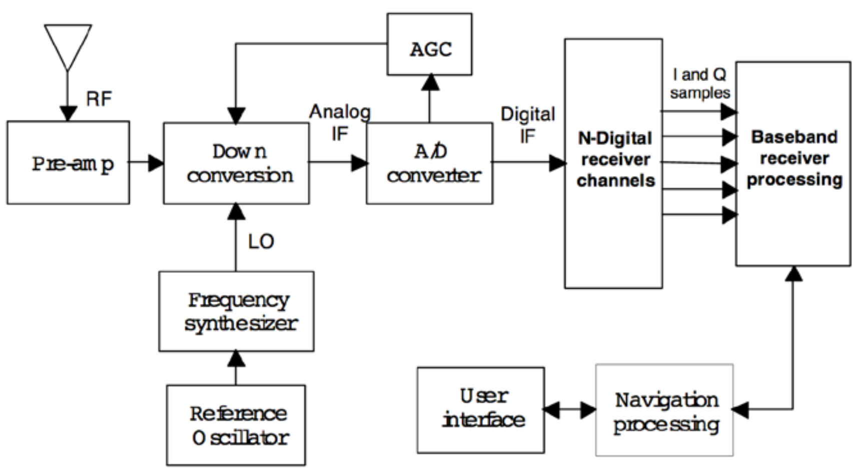
$$y_R(t) = A_R \cdot d(t-\tau(t)) \cdot g(t-\tau(t)) \cdot \cos\left[\omega_{L1}\left(t-\tau(t)\right)+\theta\right] + n(t)$$

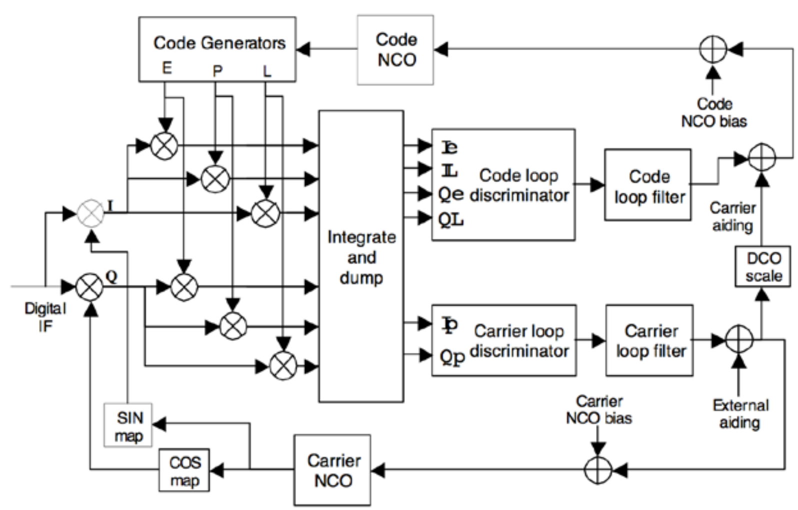
- Delay $\tau(t)$ given by path length over speed-of-light-in-vacuum plus additional terms due to reduced speed-of-light in ionosphere and troposphere.
  - Frequency dependence of ionosphere delay (neglected above) causes slight difference in code and carrier delay ("code-carrier divergence")
- Doppler shift proportional to delay rate-of-change $\omega_d = -\omega_{L1}\dot{\tau}(t)$
- Signal power below ambient noise power in received bandwidth
- May also receive the signal along multiple paths (multipath)

GPS Receivers: Acquisition and Tracking

- To detect the GPS signal and recover the navigation data, receiver “correlates” received (downconverted and digitized) signal with locally generated replica of received signal
- PRN codes for satellites are known and “orthogonal” to other codes and self at non-zero time delay
- Acquisition involves search over range of delay and Doppler, then synchronization to data bits and frames
- Tracking uses coupled feedback loops to maintain lock on code and carrier signal parameters





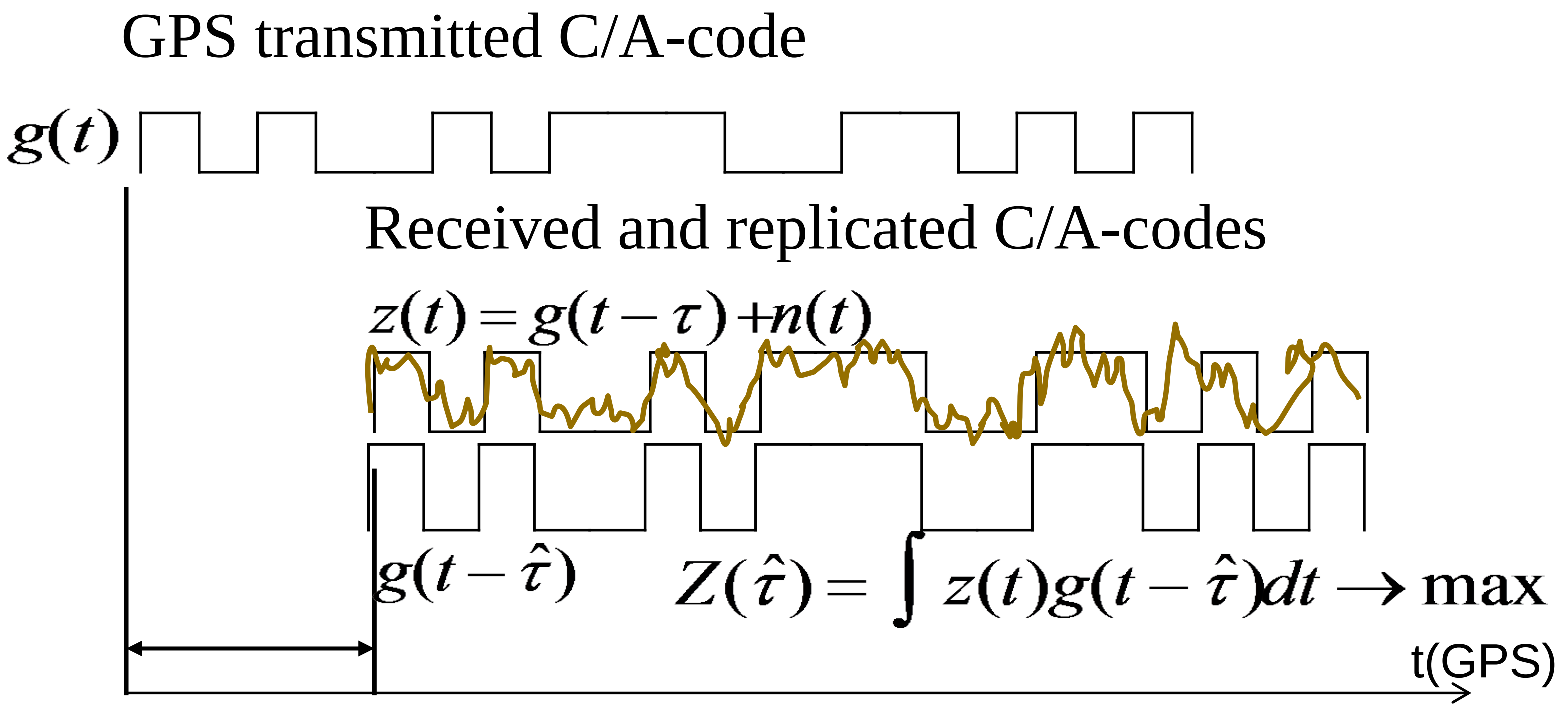


Receiver figs from Mike Moreau’s dissertation: https://ccar.colorado.edu/docs/dissertation/Moreau_2001.pdf (adapted there from P. Ward, Ch. 5 of Kaplan reference)

GPS Observables

- **Once tracking, GPS receivers typically report the following measurements**
  - Pseudorange
    - Propagation delay plus local clock bias measured using the transmitted PRN code: measured to small fraction of code “chip”: ~meter level accuracy
  - Doppler
    - Measured frequency shift of the received beat carrier signal
  - Carrier Phase
    - Measured fractional and accumulated whole cycle phase of the beat carrier signal, can be measured to small fraction of 19cm cycle: mm precision
  - C/N_0
    - Carrier to noise spectral density estimate in dB-Hz

Generating pseudorange at receive time t



- Adjust local code delay to maximize correlation Z
- At receive time t, observe "code phase" $t_T = t - \hat{\tau}$ of input-synchronized replica. This is a direct estimate of the *time-of-transmission*
- Receiver has only biased estimate of receive time $\hat{t} = t + \delta t$
- Compute a "Pseudorange" $\rho_k = c\left(\hat{t} - t_T\right) = c\hat{\tau} + c\delta t$

Measurement Equation (cont)

- Measured (code) pseudorange to GPS k comprises:

$$\rho_k = c\tau_k + c\left[\delta t - \delta t_k\right] + \varepsilon_k$$

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

Receiver position and clock error are to be solved for

- 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)

- Carrier phase measurement equation is similar, but
  - Adds whole cycle integer ambiguity term Nλ
  - Ionosphere delay has opposite sign
  - Noise on the order of *millimeters* instead of meters

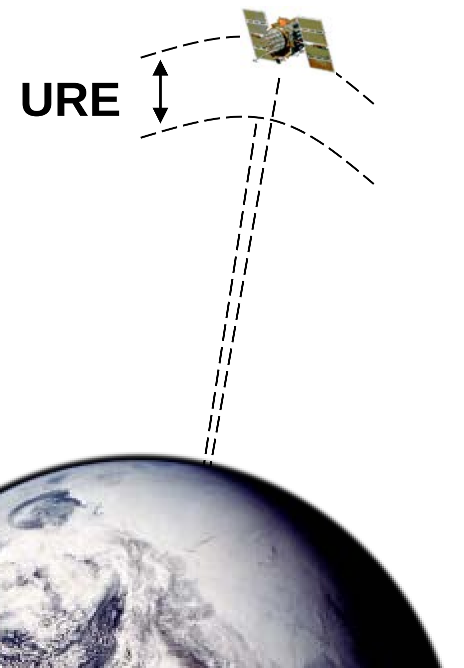
Solution Accuracy

- 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.

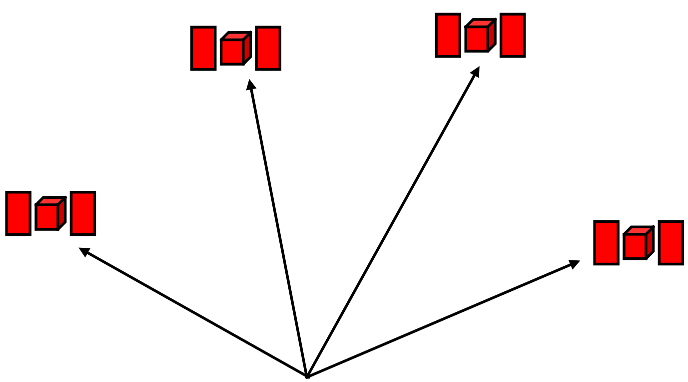
Ranging Error

- 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

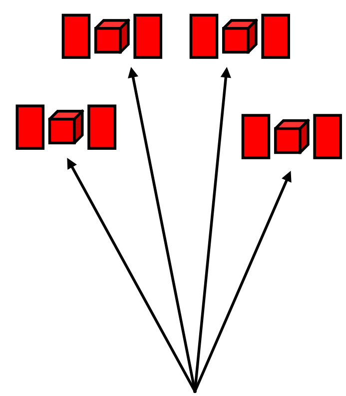


Geometry – Dilution of Precision

- 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 (Low) GDOP



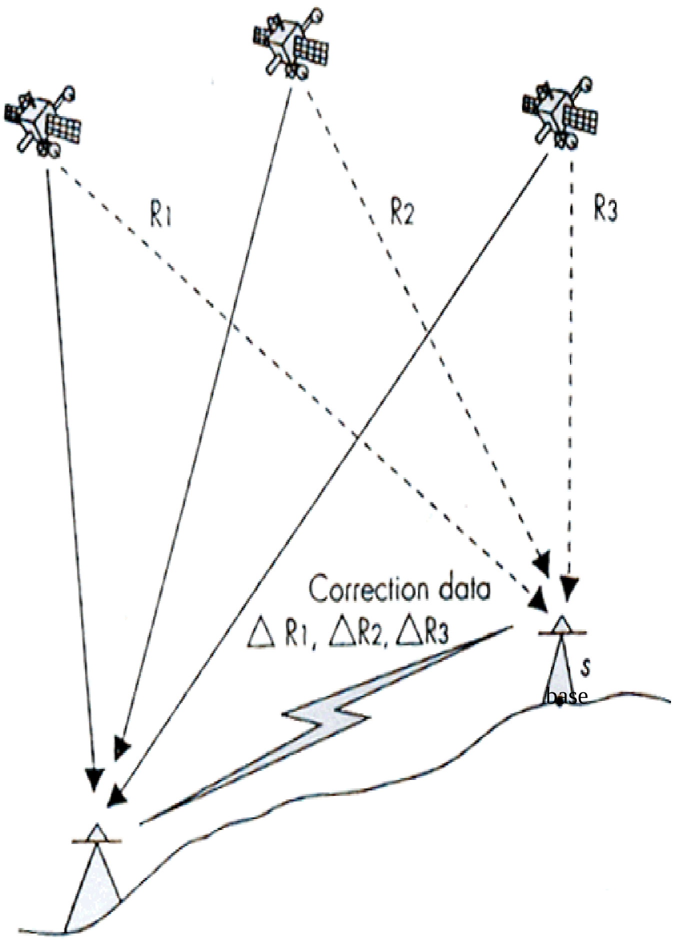
Poor (High) GDOP

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

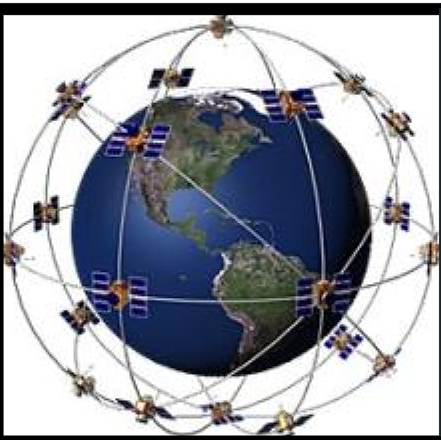
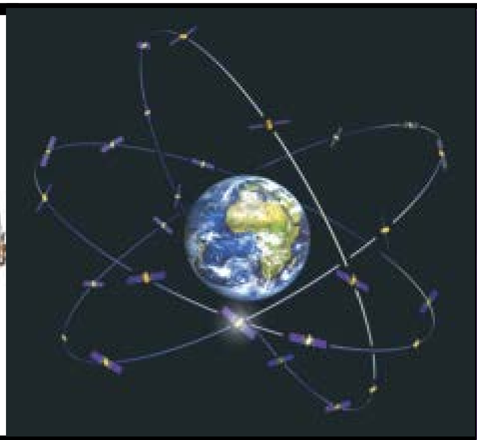
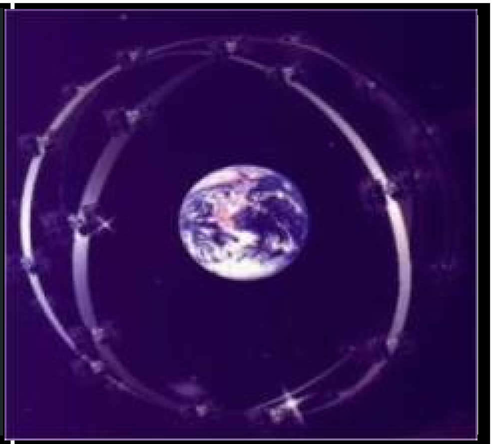
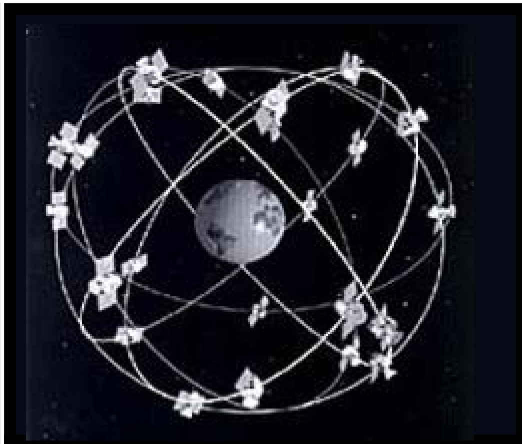
- **Receivers in close proximity can have their common error sources cancel**
  - Ionosphere and troposphere delays
  - Satellite orbit error
  - Satellite clock error
- **Single Differences (SD)** – formed from like measurements of the same GPS satellite made from two receivers
  - Removes errors common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

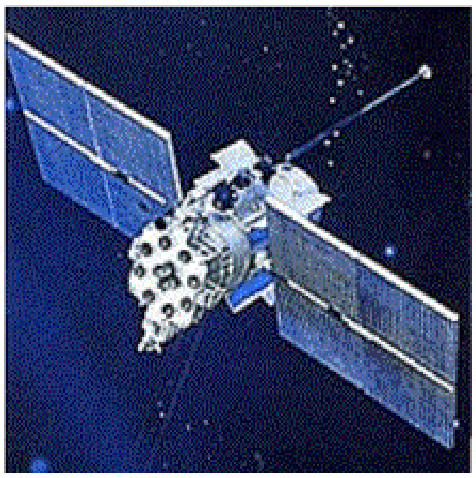


Other GNSS Systems and Augmentations

Global GNSS Constellations

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


GLONASS: GLObal NAvigation Satellite System

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/

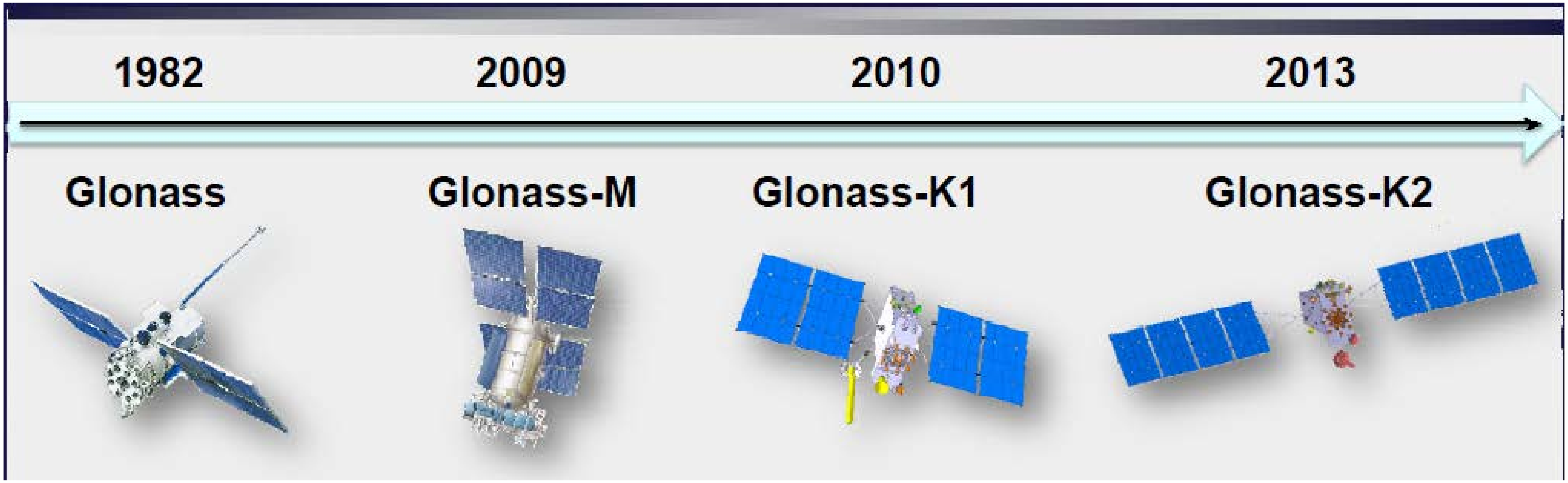
GLONASS Status

- GLONASS Constellation Status (24 Apr 2017)
  - 27 Total satellites in constellation
  - 24 Operational
  - \- In Commissioning Phase
  - 1 In Maintenance
  - 1 Under check by Satellite Prime Contractor
  - 1 On-orbit spares
  - 1 Flight Test Phase
- Most recent launch in 29 May 2016
- GLONASS accuracy has improved significantly over the past five years; approaching performance of GPS

https://www.glonass-iac.ru/en/GLONASS/

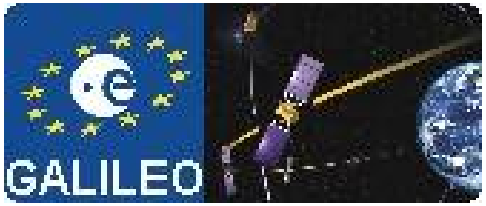
GLONASS Modernization

- 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

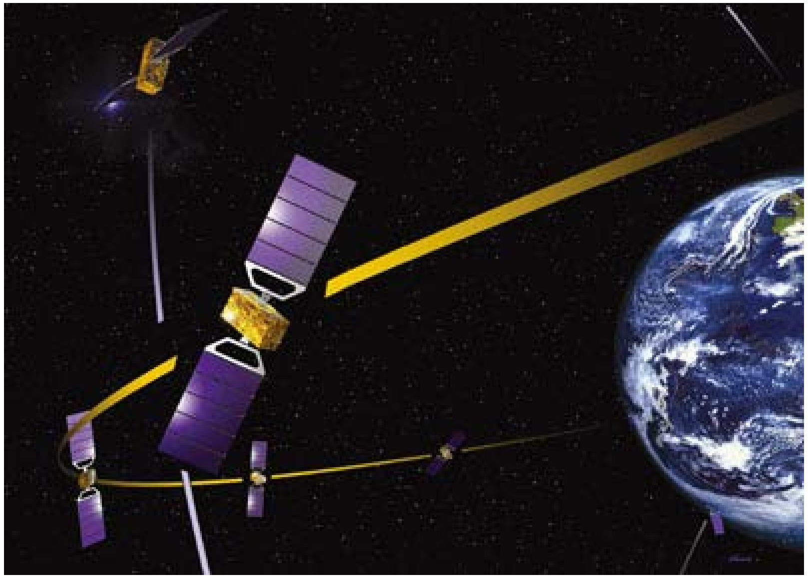


For more information, see: GLONASS Status and Progress, Sergey Revnivykh, 19 September 2011
http://www.navcen.uscg.gov/pdf/cgsicMeetings/51/3_GLONASS_CGSIC_Oleynik.pdf

GALILEO

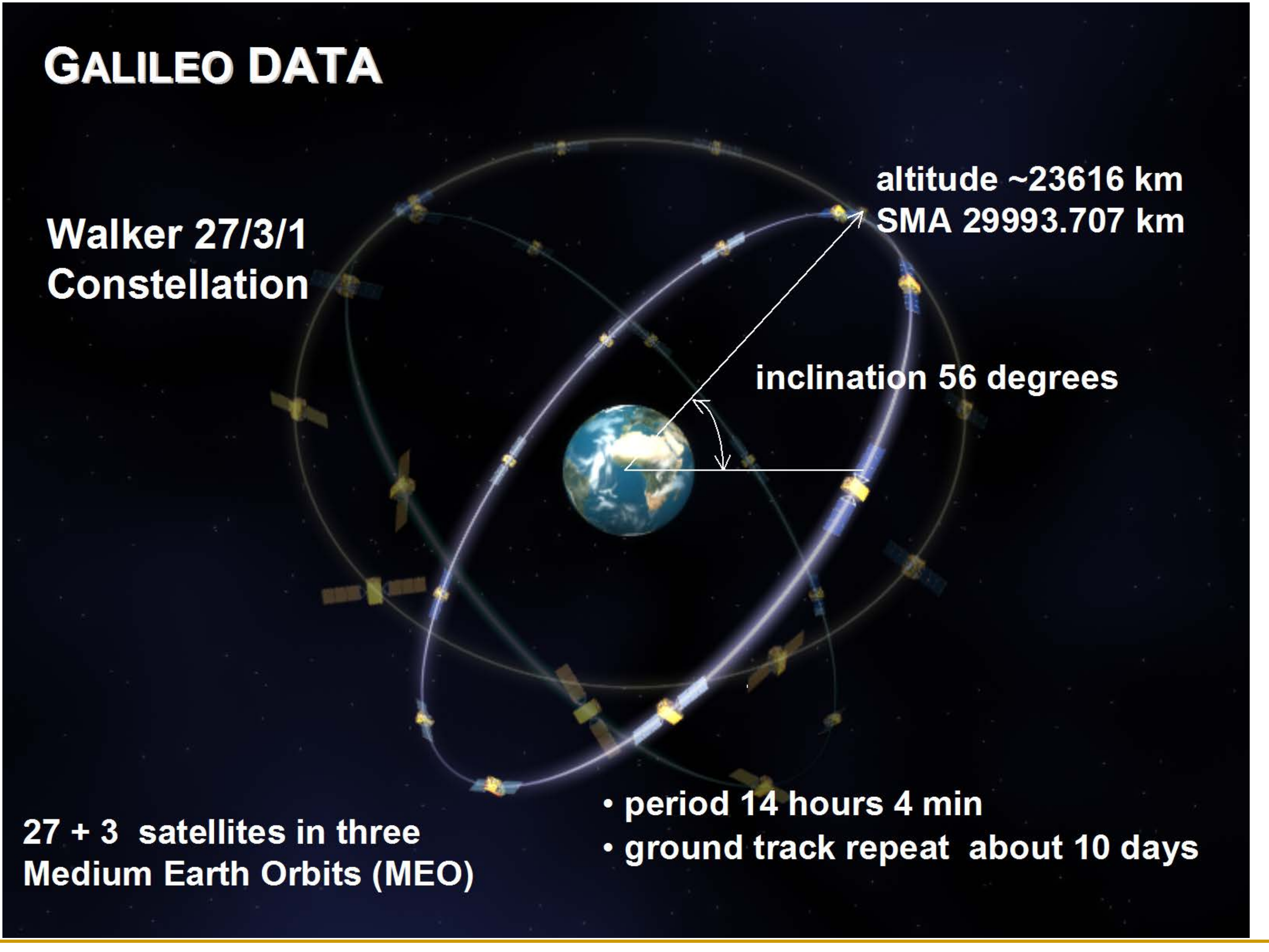


- Galileo is a joint initiative of the European Commission (EC) and the European Space Agency (ESA).
- It will be interoperable with GPS and GLONASS, the two other global satellite navigation systems.
- Consists of 30 medium Earth orbit satellites, associated ground infrastructure, and regional/local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

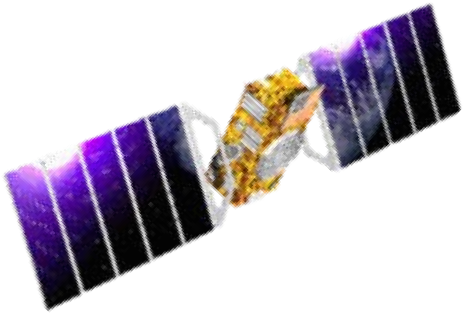


http://www.esa.int/esaNA/galileo.html

Galileo Constellation Configuration

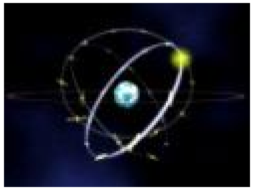


Galileo Implementation Plan

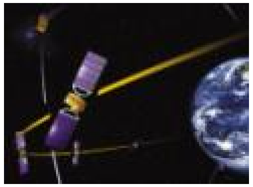


Full Operational Capability
27 (+3) Galileo satellites
~2020

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

Galileo Status

- ESA's first two navigation satellites, GIOVE-A and –B, were launched in 2005 and 2008 respectively
  - Reserved radio frequencies set aside for Galileo by the International Telecommunications Union
  - Tested key Galileo technologies
- In-Orbit Validation (IOV) phase
  - First two of four operational satellites launched October 2011 to validate the Galileo concept in both space and on Earth.
  - Two more launched in October 2012. Galileo only solutions demonstrated in 2013.
- Full Operational Capability (FOC)
  - Fourteen FOC satellites launched so far, including six in 2016!
  - The first two were initially inserted into incorrect orbit, have been recovered into usable orbit.
  - Fully deployed Galileo system consists of 30 satellites (27 operational + 3 active spares), positioned in three circular Medium Earth Orbit (MEO) planes ~2020

http://www.esa.int/esaNA/galileo.html
https://www.gsa.europa.eu/european-gnss/galileo/system-status

Chinese BeiDou System

- The **BeiDou** system (also known as **Compass**) will include 5 geostationary orbit (GEO) satellites and 30 non-GEO 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 (BDS-2) – provision of satellite navigation services for Asia-Pacific region
  - 16 satellites launched since 2007, with six launches in 2012
  - BeiDou's current constellation providing regional navigation services
  - Consists of five geostationary (GEO), five inclined geosynchronous orbit (IGSO), and four middle Earth orbiting (MEO) spacecraft
- Third phase (BDS-3) extends to global coverage by 2020
  - Since 2015, 5 BDS-3 sats have been launched, most recent 29 March 2016

http://en.beidou.gov.cn/

http://www.unoosa.org/pdf/icg/2014/icg-9/icg9-04.pdf

Regional Satellite Navigation Systems

- Navigation with Indian Constellation (NAVIC); formerly Indian Regional Navigational Satellite System (IRNSS)
  - Autonomous regional satellite navigation system consisting of 7 satellites and ground segment
  - Developed by Indian Space Research Organization
  - Seventh satellite launched 28 April 2016.
- 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)
- Russian System of Differential Corrections and Monitoring (SDCM)

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.

International Coordination

- International coordination is critical to ensure compatibility and interoperability
- US has bilateral agreements or joint statements with all major international GNSS service providers
- International committee on GNSS (ICG) Established in 2005 under the umbrella of the United Nations to provide forum for discussion
  - Purpose is to promote voluntary cooperation on matters of mutual interest in order to ensure greater compatibility, interoperability, and transparency among GNSS systems
  - 11th ICG held in Russia in Nov 2016, 10th held in Boulder/UCAR

http://www.gps.gov/cgsic/meetings/2014/clore.pdf
http://www.unoosa.org/oosa/en/SAP/gnss/icg.html

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 C/A – GPS Course Acquisition Code at 1.57542 GHz
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

Official U.S. Government information about GPS

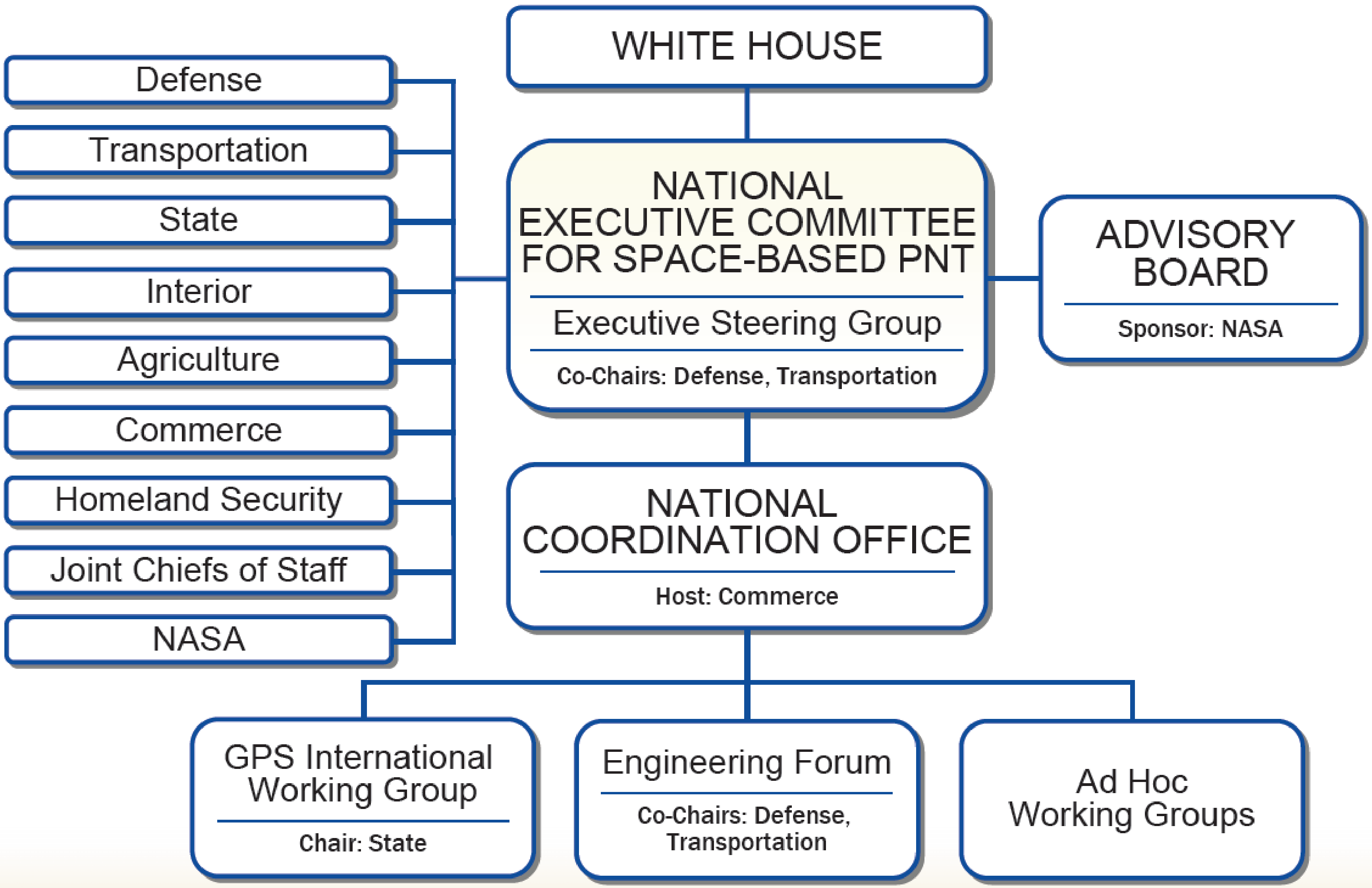
GPS References

- National Executive Committee for Space-Based Positioning, Navigation, and Timing (PNT)
  - http://pnt.gov/
- Federal Aviation Administration – Navigation Services
  - http://gps.faa.gov/index.htm
- US Coast Guard Navigation Center
  - http://www.navcen.uscg.gov/
- Civil GPS Service Interface Committee (CGSIC) Meetings
  - http://www.navcen.uscg.gov/?pageName=cgsicMeetings
- NASA Global Differential GPS System
  - http://www.gdgps.net/

GPS References (continued)

- Elliott D. Kaplan, Christopher J. Hegarty, ***Understanding GPS: Principles and Applications***, Artech House Publishers, 2006.
- P. Misra, P. Enge, ***Global Positioning System: Signals, Measurements, and Performance***, Ganga-Jamuna Press, 2001.
- B.W. Parkinson et al. (editors), ***Global Positioning System: Theory and Applications***, Vol. 1&2, Progress in Astronautics and Aeronautics, 1997.

U.S. Space-Based PNT Organizational Structure



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

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

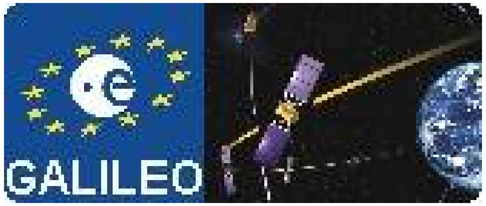
- Several Command Tracking Stations (CTS) throughout Russia
  - St. Petersburg, Ternopol, Yeniseisk, Komsomolsk, Balkhash
  - track satellites in view and accumulate ranging data and telemetry from the satellite signals
  - transmit updated information to satellites, as well as other control information
  - 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



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- It will be interoperable with GPS and GLONASS, the two operational global satellite navigation systems.
- Consists of 30 medium Earth orbit satellites, associated ground infrastructure, and regional/local augmentations.
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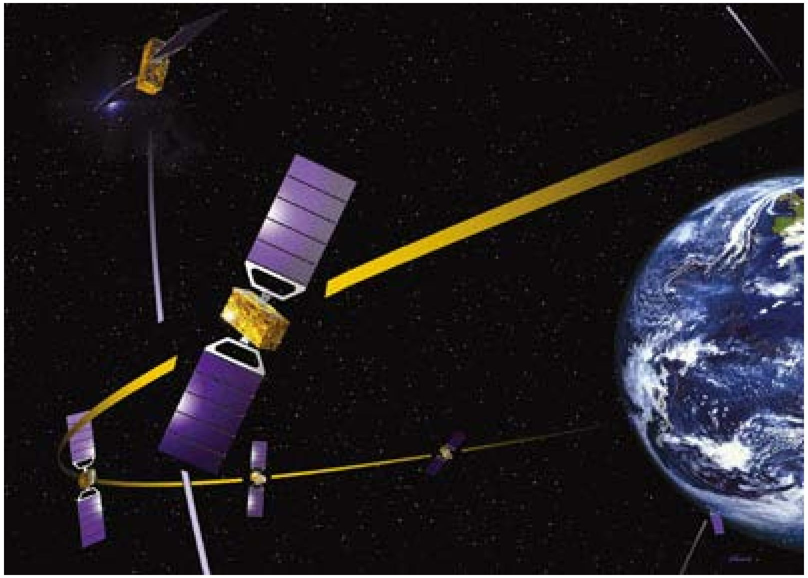
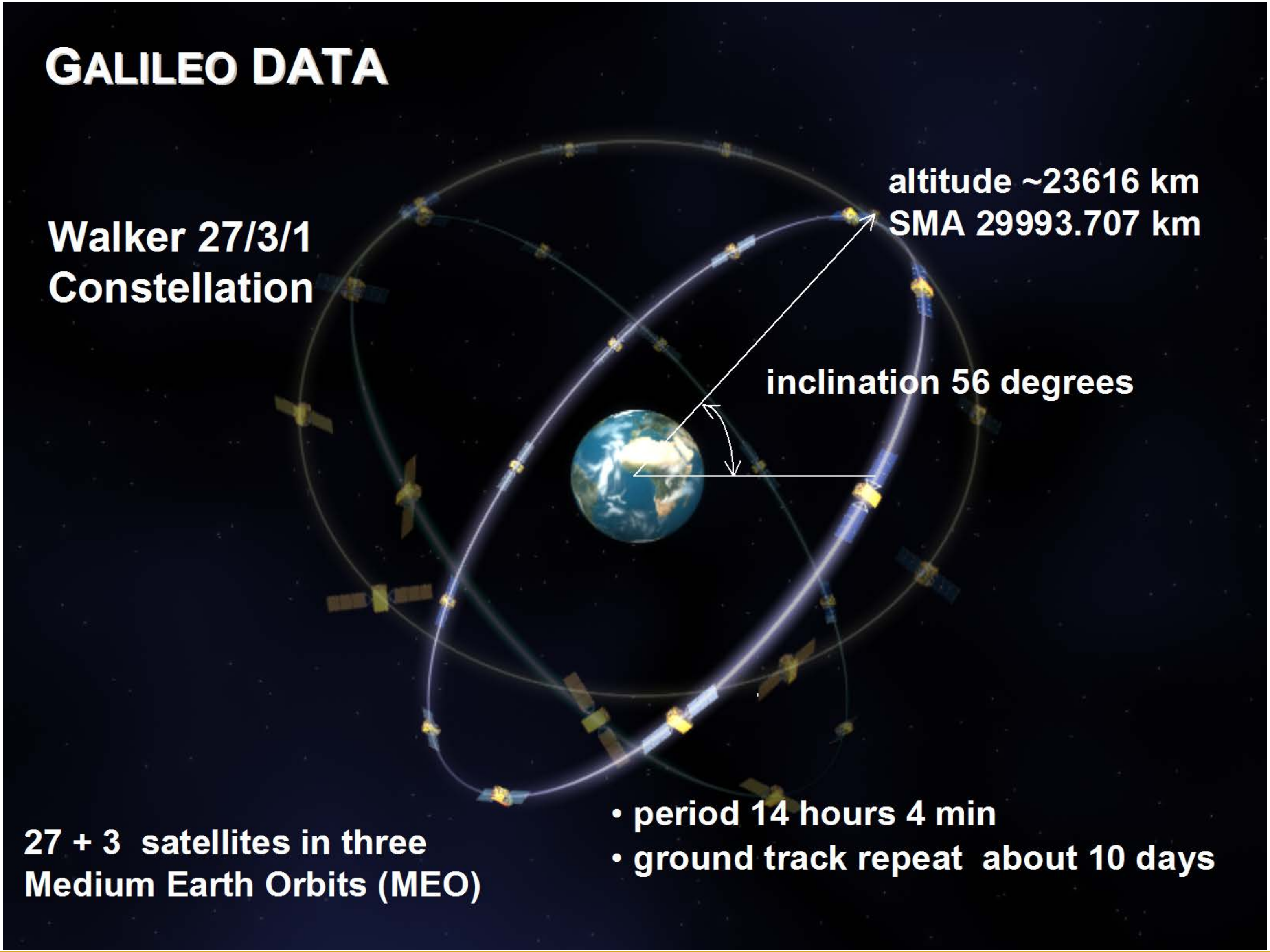


Galileo Constellation Configuration



The GALILEO Satellite Services

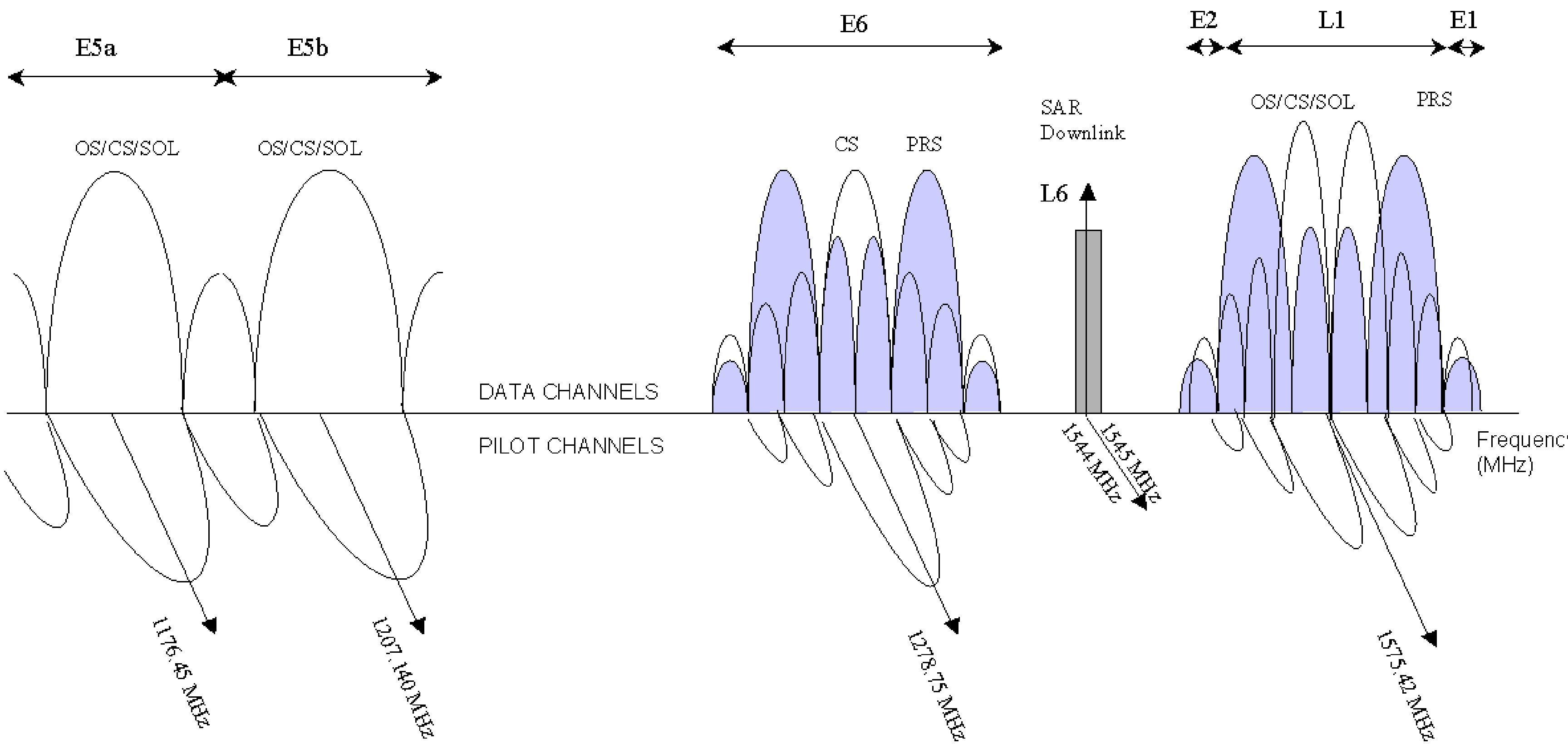
Position, Velocity and Time Services:

- **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

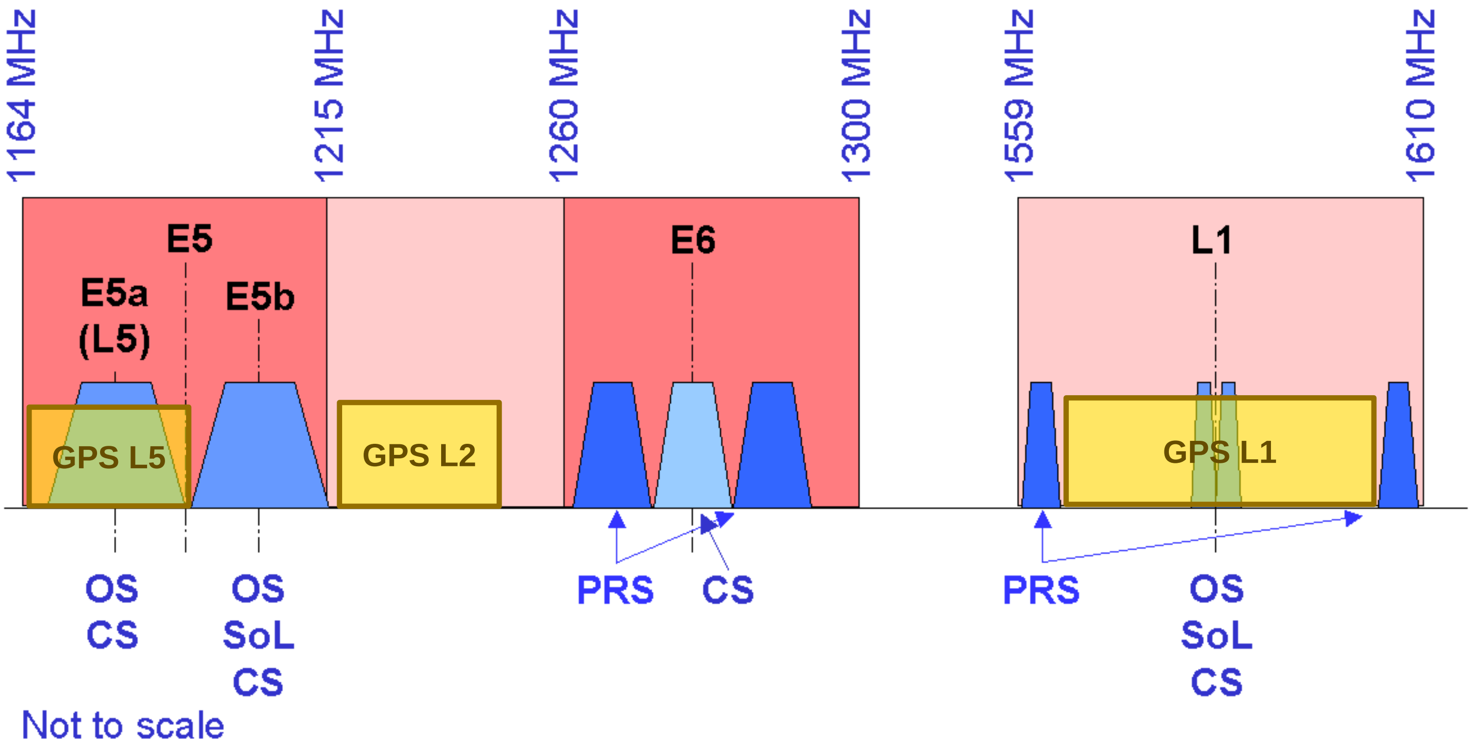


Each Galileo Satellite will broadcast 10 navigation signals, making up the open (OS), safety-of-life (SOL), commercial (CS) and public regulated services (PRS)

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



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

Galileo System Design

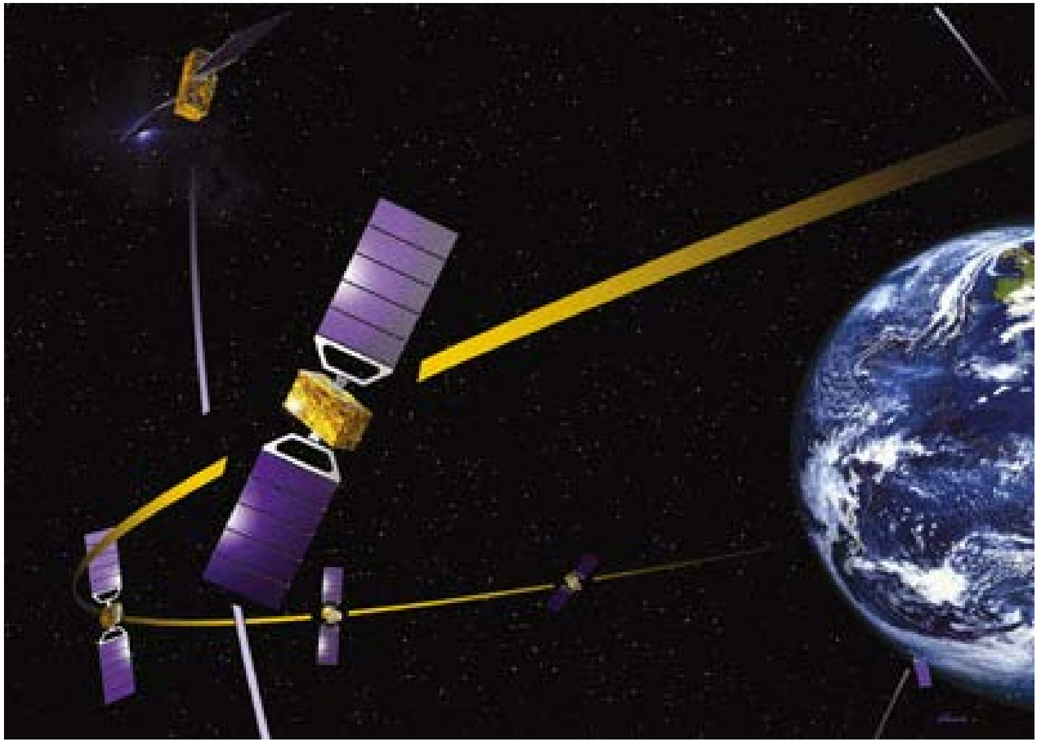
- Galileo Terrestrial Reference Frame (GTRF):
  - An independent realization of the International Terrestrial Reference System (ITRS) established by the Central Bureau of the International Earth Rotation Service (IERS).
  - Differences between WGS84 and GTRF ~ a few cm.
- Galileo System Time (GST):
  - 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
  - <u>Includes an agreement to establish a common civil signal at the L1 frequency</u>
- Additional availability, precision, and robustness provided by complementary systems

GALILEO References

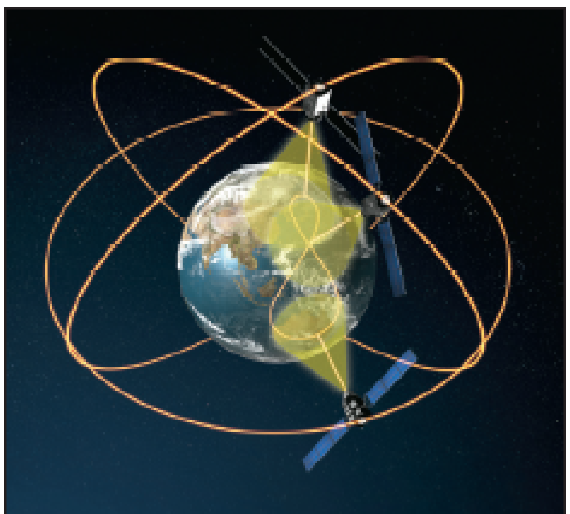
- Further information can be found here:
  - http://www.esa.int/esaNA/index.html



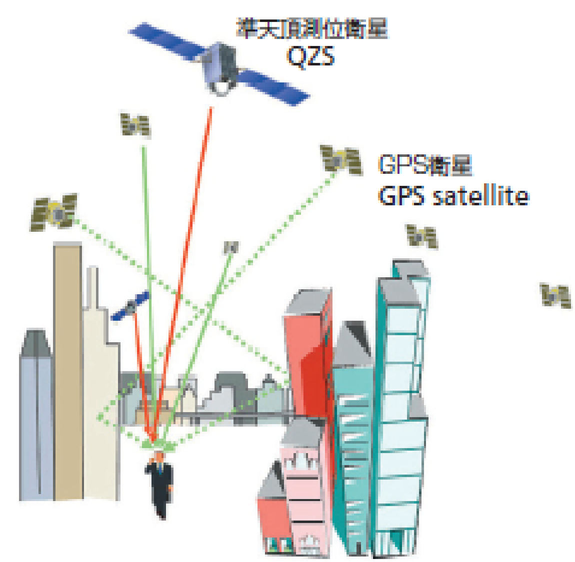
Quasi-Zenith Satellite System (QZSS)

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

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
- Seventh satellite launched 28 April 2016.
- Completed and operational in 2016

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

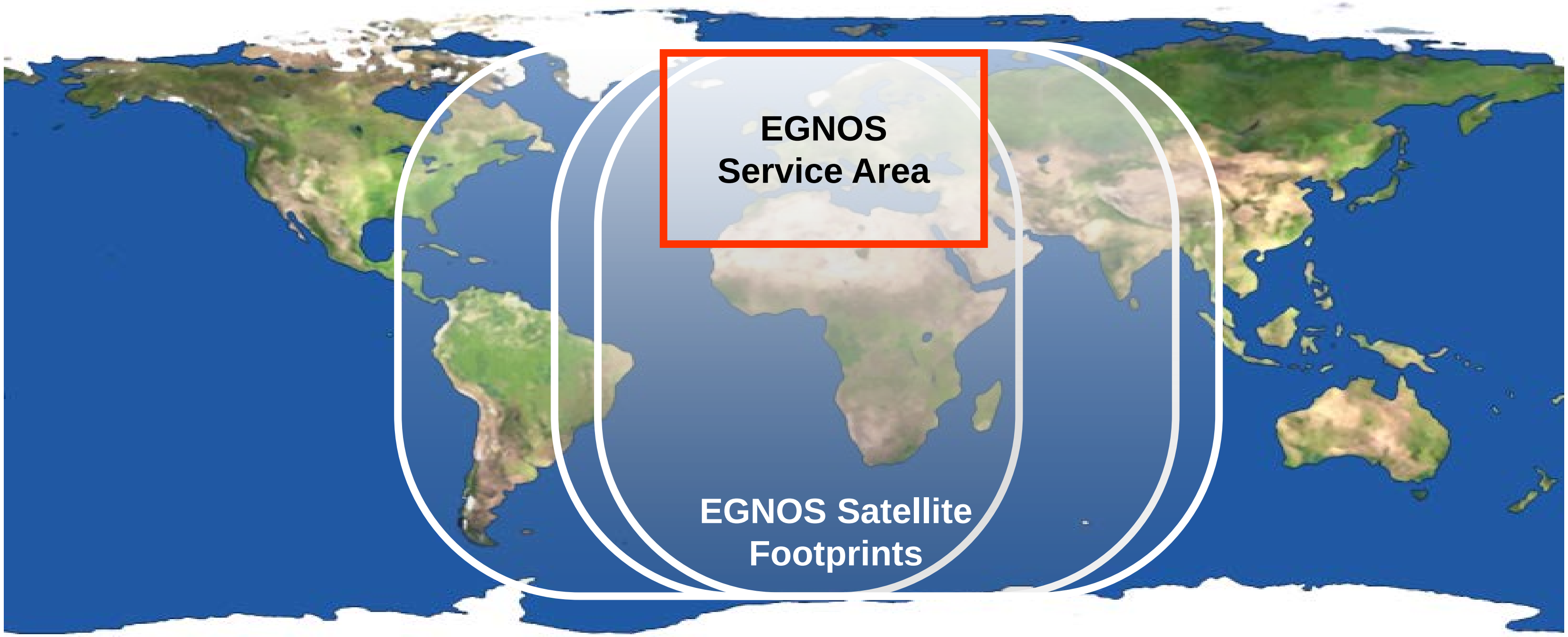
Indian GPS Aided Geo Augmented Navigation (GAGAN)

- 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 completed in 2013

http://www.oosa.unvienna.org/pdf/icg/2008/expert/2-3.pdf
http://www.isro.gov.in/update/03-jan-2014/gagan-system-certified-rnp01-operations

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.



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