Update on GNSS

Time Creation and Distribution - How well does it really work?

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Prague

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Outline: GNSS in Time Creation and Distribution

- Update on the GNSS “Revolution”
  - GPS
  - GLONASS
  - Galileo
  - Beidou
- Conclusions
- Extra Slides

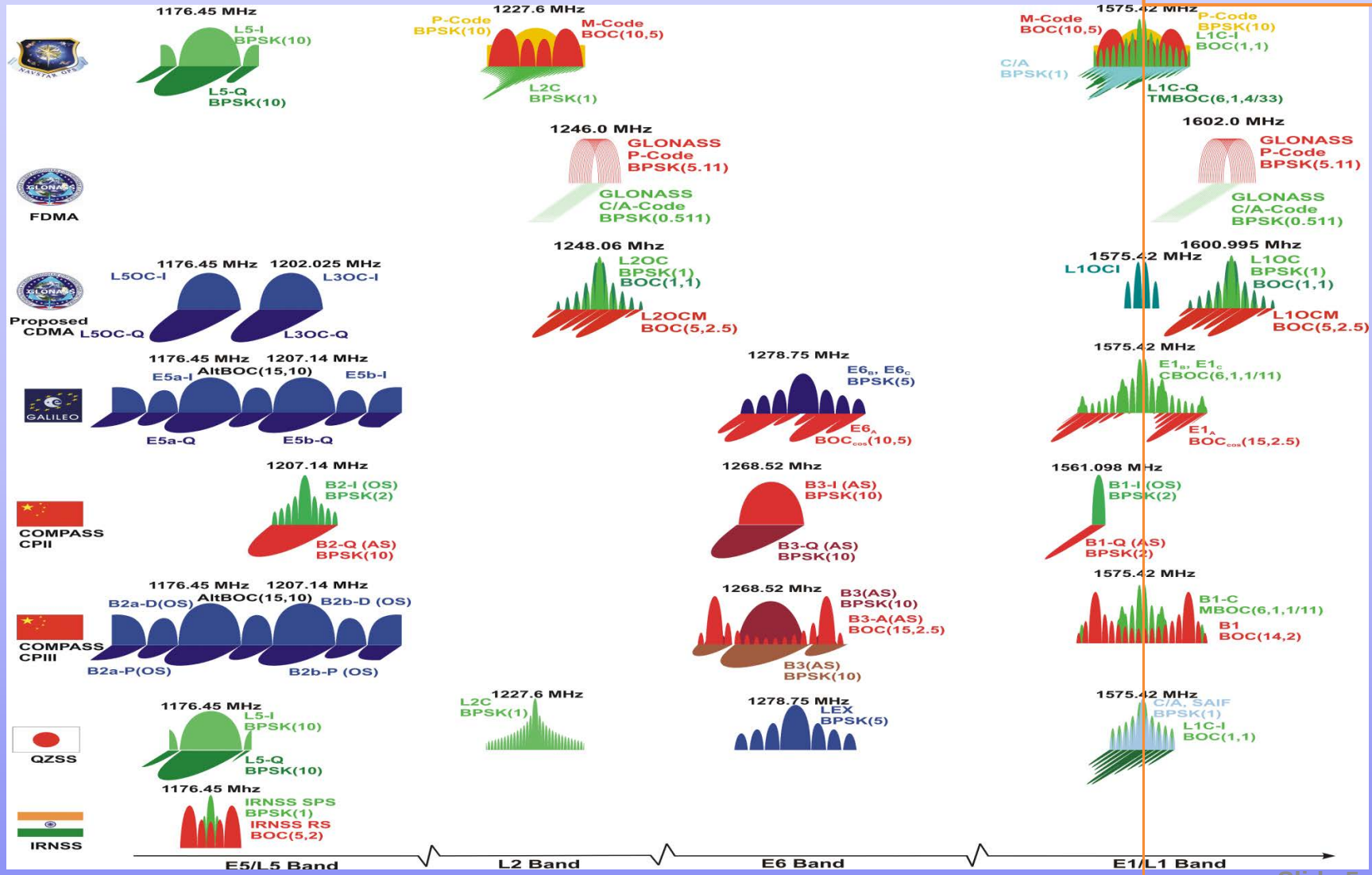
Update What?

- GPS original civilian signal, C/A, not meant to be used
  - New signals, satellites, ground control
  - Specific designs for international civilian use and inter-operability with other systems
- GLONASS original civilian signal FDMA, system issues with USSR collapse
  - Replenishment, improved accuracy, reliability
  - New satellites with CDMA + FDMA signals
- Galileo – see next talk
- Beidou developing from regional to global system
  - Initial focus on use in China
  - Soon to be global, designed to be interoperative

The Family of Global Navigation Systems: Global Source of UTC, but Each is Slightly Different

GPS	Galileo	GLONASS	Beidou/Compass
US	EU	Russia	China
(24+, Now 31)	(27, Now 8-10)	(24, Now 24-26)	(35, Now 5 GEO, 8 IGSO, MEO 6-7 out of 24)

Spectra of GNSS's



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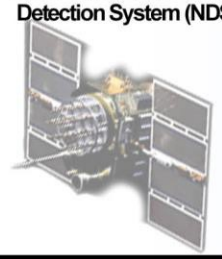
GPS Modernization

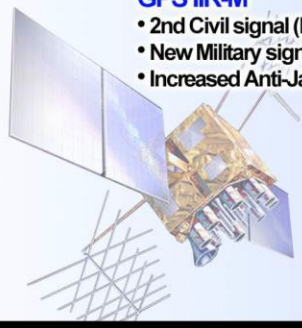
SPACE AND MISSILE SYSTEMS CENTER

Space System (Satellites)

Legacy (GPS IIA/IIR)
- Basic GPS
- NUDET (Nuclear Detonation) Detection System (NDS)

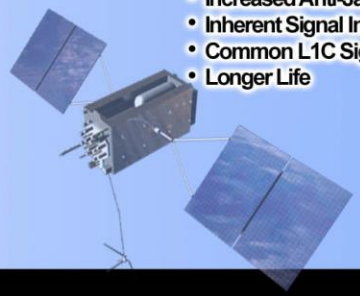


GPS IIR-M
- 2nd Civil signal (L2C)
- New Military signal
- Increased Anti-Jam power



GPS IIF
- 3rd Civil Signal (L5)
- Longer Life
- Better Clocks

GPS III
- Accuracy & Power
- Increased Anti-Jam power
- Inherent Signal Integrity
- Common L1C Signal
- Longer Life



Ground System

Legacy (OCS)
- Mainframe System
- Command & Control
- Signal Monitoring

AEP
- Distributed Architecture
- Increased Signal Monitoring Coverage
- Security
- Accuracy
- Launch And Disposal Operations

OCX Block 1
- Fly Constellation & GPS III
- Begin New Signal Control
- Upgraded Information Assurance

OCX Block 0
- GPS III Launch & Checkout

GPS III Contingency Ops (COps)
- GPS III Mission

OCX Block 2+
- Control all signals
- Capability On-Ramps
- GPS III Evolution

User Equipment System (Receivers)

Legacy (PLGR/GAS-1/MAGR)
- First Generation System

User Equipment
- Improved Anti-Jam & Systems
- Reduced Size, Weight & Power

Upgraded Antennas
- Improved Anti-Jam Antennas

Modernized
- M-Code Receivers
- Common GPS Modules
- Increased Access/ Power with M-Code
- Increased Accuracy
- Increased Availability
- Increased Anti-Tamper/ Anti- Spoof
- Increased Acquisition in Jamming

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=3468589

•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 ~2017 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+ will add
  - Laser Retro-reflector Array
  - Search and Rescue payload
- GPS III SV11+ is an open procurement

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 – 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 replacing original control segment mainframes
  - 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)
  - Supports GPS III and all modernized signals
  - Multiphase rollout currently planned for 2016-2018

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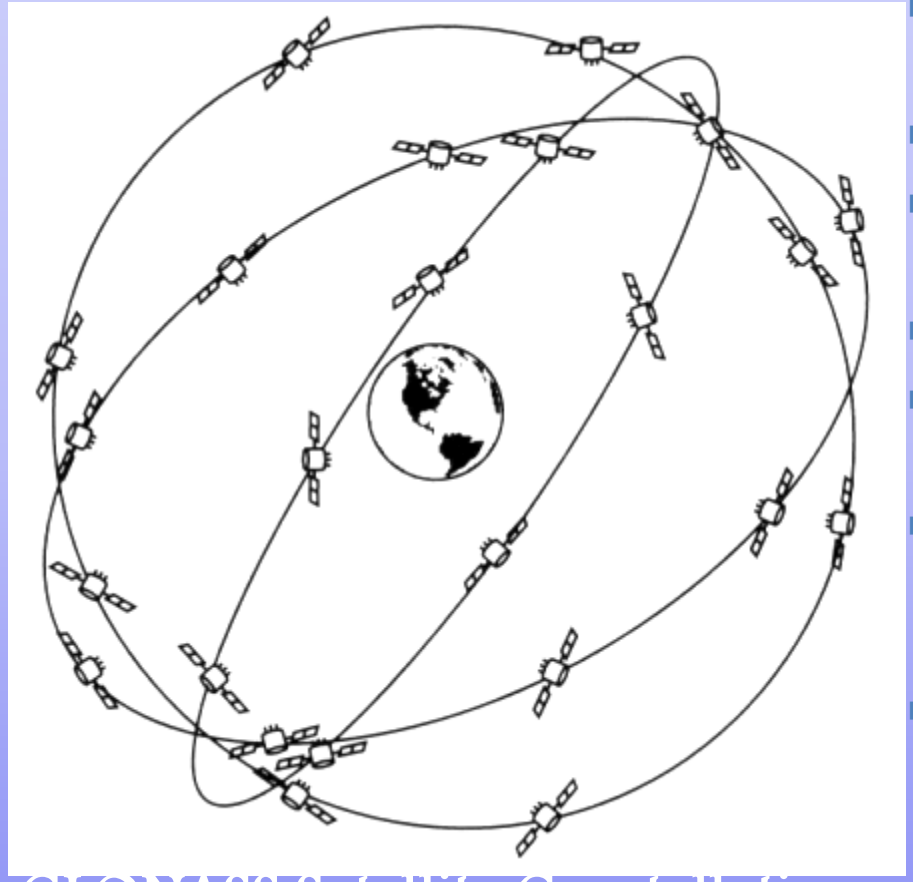
GLONASS: GLObal NAvigation Satellite System



•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 (07 Oct 2016)
  - 28 Total satellites in constellation
  - 24 Operational
  - - In Commissioning Phase
  - - In Maintenance
  - - Under check by Satellite Prime Contractor
  - 2 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 on K-series for improved interoperability with other GNSS systems
  - The first satellite of the third generation, GLONASS-K1, was launched on February 26 2011
  - Continue to broadcast legacy FDMA signals
  - New GLONASS K satellites with improved accuracy and longer design life
  - GLONASS-K2 satellites generation planned for 2018
  - Improvements to ground control system

Source: http://www.navipedia.net/index.php/GLONASS_Future_and_Evolutions

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Chinese BeiDou Navigation Satellite System (BDS)

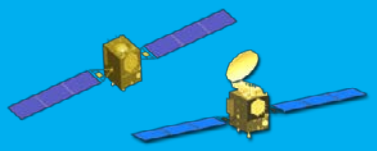
- The **BeiDou** system (also known as **Compass***)* will include 5 geostationary orbit (GEO) satellites and 30 non-GEO satellites
- BeiDou will provide three carrier frequencies foreseen to be interoperable with other systems.
- Demonstration Phase
  - Completed in 2003 with launch of 3 Geostationary satellites
- Second Phase (BeiDou-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
  - Currently 5 geostationary (GEO), 5 inclined geosynchronous orbit (IGSO), and 6-7 out of 24 middle Earth orbiting (MEO) spacecraft
- Third phase extends to global coverage
  - Most recent launch 29 March 2016

•http://www.beidou.gov.cn/

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

BDS - System Components

space segment



5 GEO satellites
3 IGSO satellites
27 MEO satellites

ground segment

Master Control Stations(MCS)
Uplink Stations (US)
Monitoring Stations (MS)

user segment

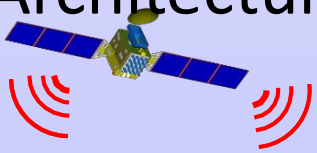
BDS terminals compatible with other GNSS

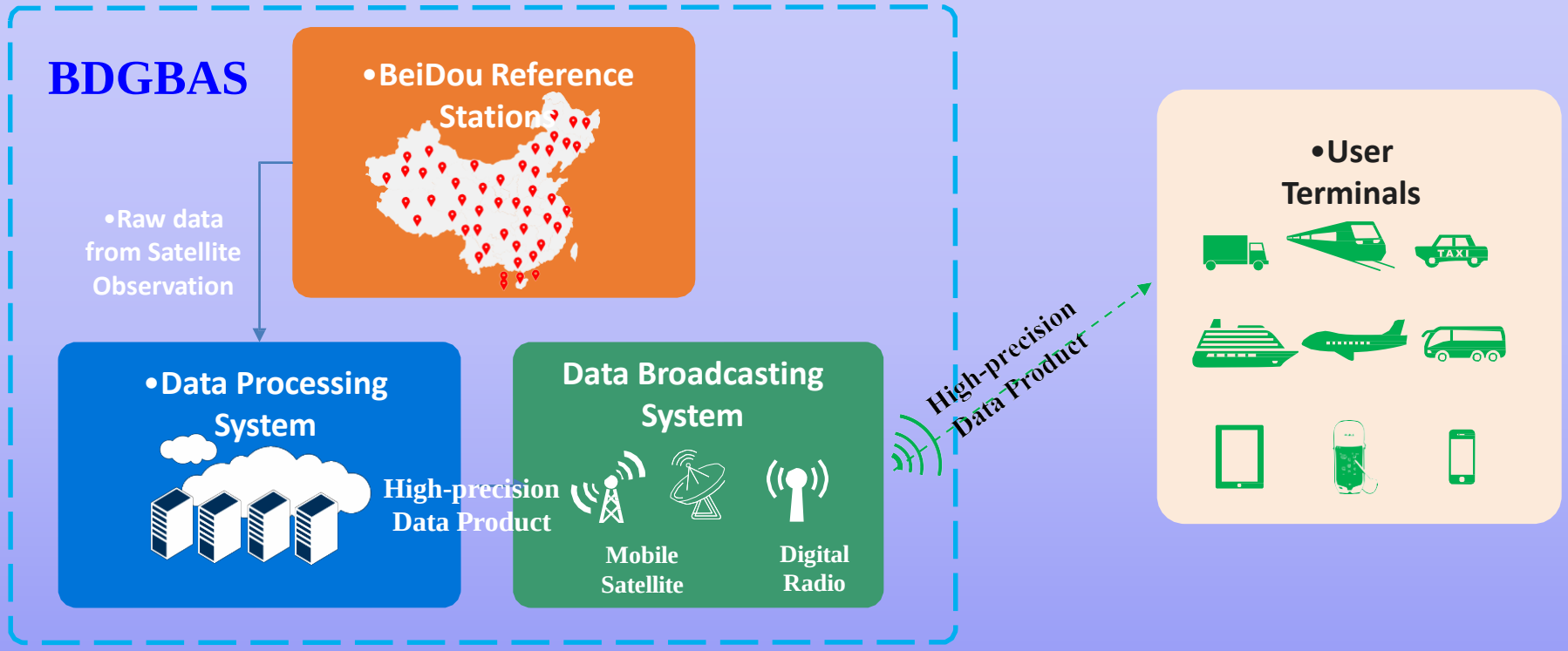
- ✓ BDS is comprised of three major components: space segment, ground control segment and user segment.
- ✓ BDS is able to provide four types of services, namely, open, authorized, wide area differential and short message services.
- ✓ The positioning accuracy is better than 10 meters, the timing accuracy is better than 20 nanoseconds, and the velocity accuracy is better than 0.2 meters per second.

Fundamental Policies

- Provide open services free of charge for users.
- Maintain and enhance the system, and improve service performance continuously, and offer services with higher quality.
- Release open service performance specifications and related system documents on schedule, bring the function of government and market to full play, promote innovation, popularization and internationalization of BDS/GNSS applications, and lay foundation for the national strategic emerging industries.
- Adhere to the concept of development and win-win cooperation, realize compatibility and interoperability between BDS and other GNSS, give the system efficiency into full play and increase users' benefits.

National Ground-Based Augmentation System – System Architecture





China Satellite Navigation Office

ION GNSS+ 2016

September 12-16, 2106, Portland, Oregon, USA

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- Extra Slides – UTC, time transfer, references, augmentation systems

Conclusions

- GNSS are growing rapidly
  - Satellites in space, new signals
  - Ground systems, augmentations
  - Providing extremely accurate, low-cost Position, Navigation and Timing (PNT)
- GNSS signals are all vulnerable to various kinds of interference

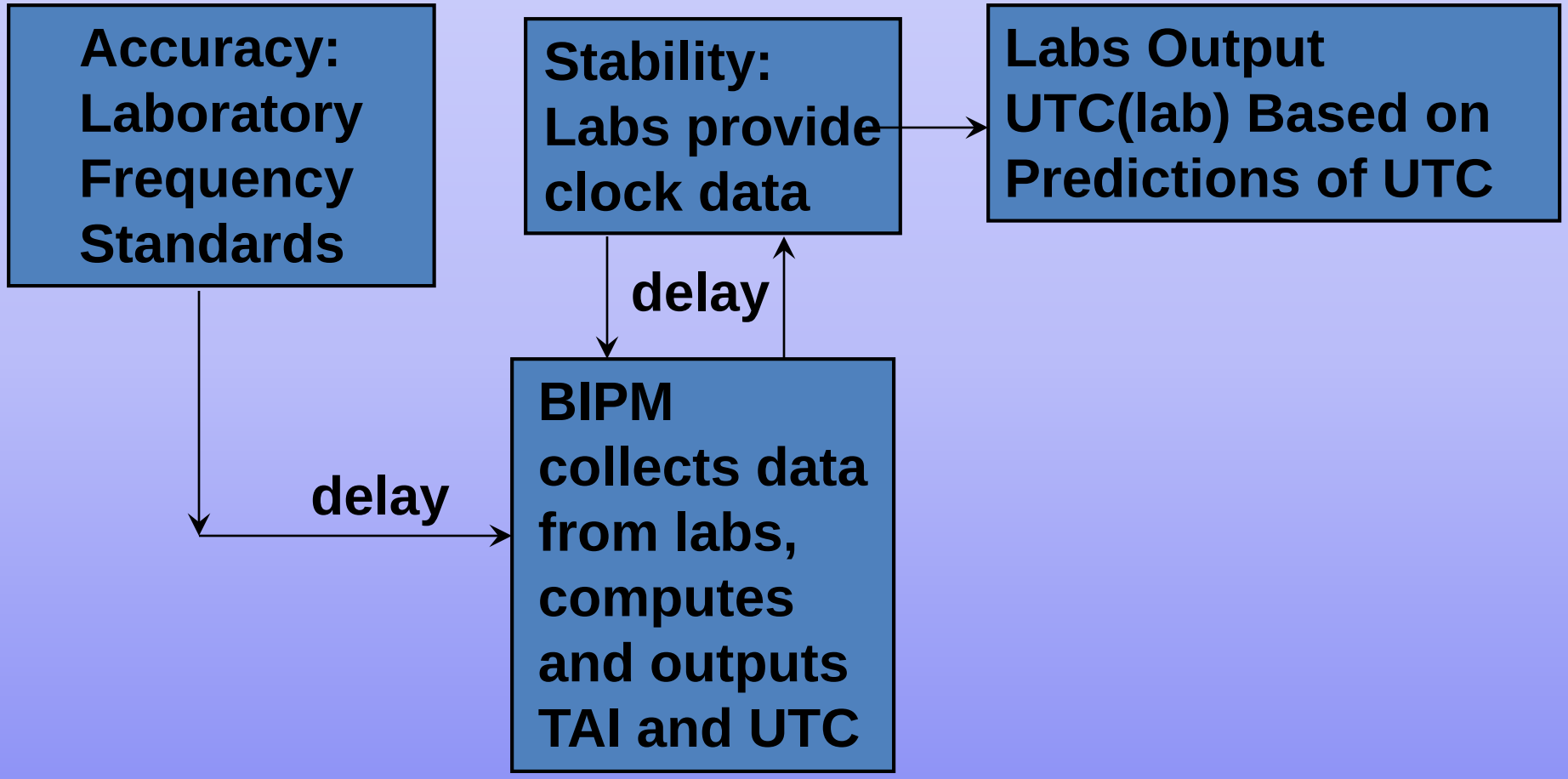
Thank you for your attention!

Questions?

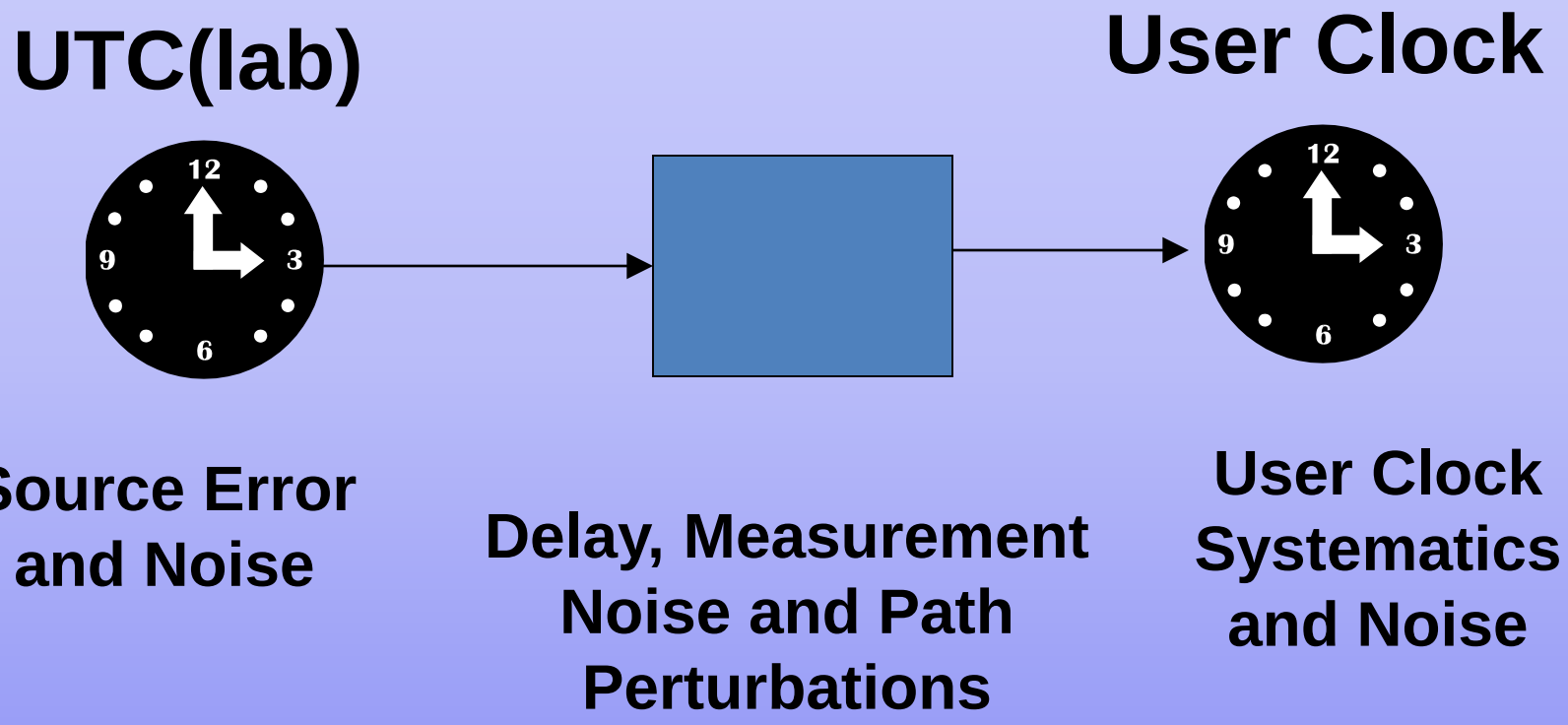
Extra slides follow FYI:
UTC, system issues, references, augmentation systems

The Generation of UTC: Time Accuracy

Any Real Time UTC is only a Prediction, A PLL with a one-month delay

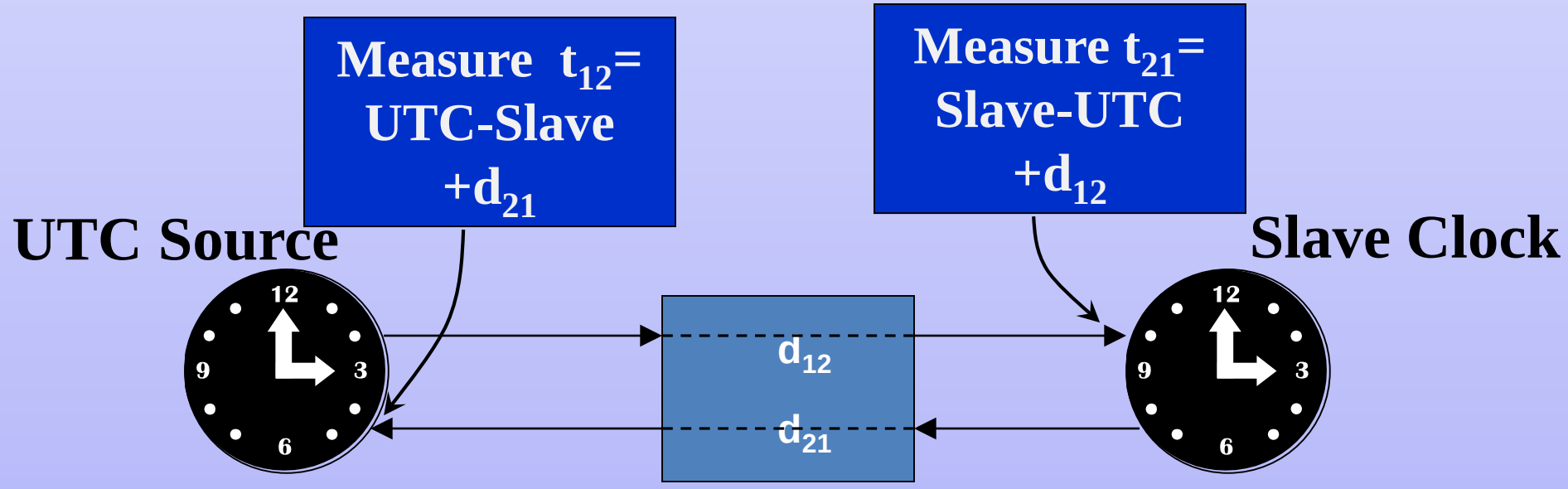


One-Way UTC Dissemination



Two -Way Comparison System

(e.g. IEEE1588 – PTP)



Source Error and Noise

Measurement Noise and Path Perturbations

Largely Reciprocal:

$d_{21} = d_{12}$

Slave Clock Systematics and Noise

Two Messages About GNSS

1. GNSS are extremely useful
    1. Constellations are growing
    2. Provide reliable, extremely accurate real-time UTC time and frequency for mostly free
    3. Excellent navigation
    4. A global > $100B industry

2. GNSS signals are dangerously vulnerable to both accidental and intentional interference

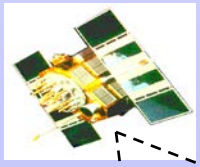
GNSS Systems: General Properties

- Position, Navigation, Timing (PNT)
- Four + synchronized timing signals from known locations in space required for navigation
- Two + frequencies measure ionosphere
- Control, Space, User Segments
- Open and Restricted Services
- All signals are weak and clustered in the spectrum
  - Allows interoperability
  - But also makes it is relatively easy to jam GNSS and spoof

Time From GNSS

- Clocks on Satellite Vehicles (SVs) are free-running
  - Data provides the offset in Time and Frequency
  - System time is offset from UTC
- The positions of the satellite and receiver are needed for the delay
- SV Clocks and positions are ***predicted*** and uploaded, for GPS about once per day

GNSS-aided Time and Frequency Systems



GNSS

T/F System

GNSS Rcvr

Compare

Tune

Quartz Crystal Oscillator

Qz Osc.

Output Freq.

Or

GPS Rcvr

Compare

Tune

Rubidium Vapor Atomic Oscillator

Rb Vapor Phy Pkg

•Qz Osc.

Output Freq.

Rb oscillator 100 to 1000 times better Holdover Performance

Courtesy H. Fruehauf, ViaLogy LLC

T/F System

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

Current GPS Constellation Status

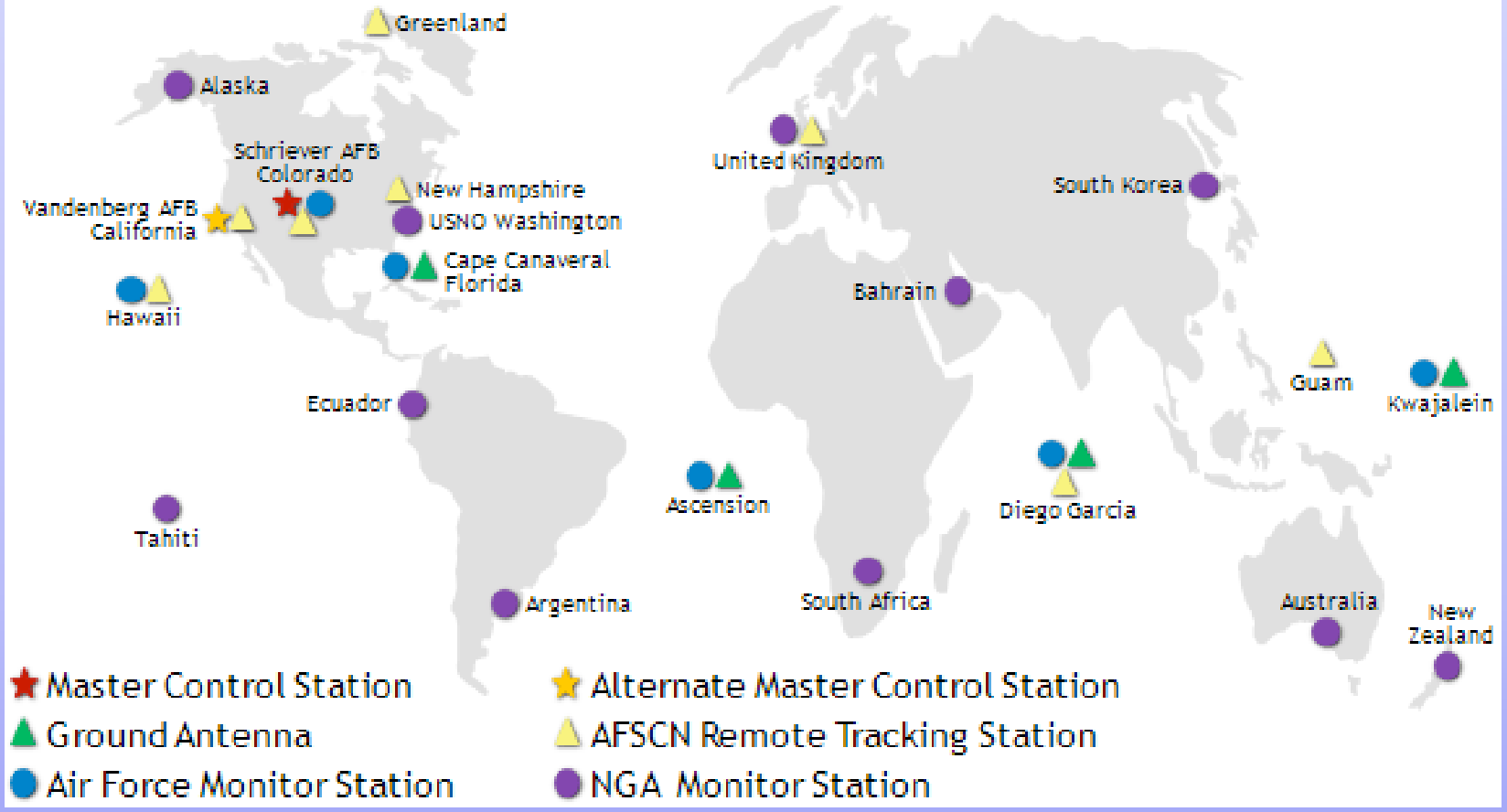
- 31 space vehicles currently in operation (2015 status in parentheses)
  - 0 (3) GPS IIA
  - 12 (12) GPS IIR
  - 7 (7) GPS IIR-M
  - 12 (9) IIF
- several additional satellites in residual status
- Continuously assessing constellation health to determine launch need
- Global GPS civil service performance 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

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 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.

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/

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.

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
  - 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)

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
  - Tenth meeting of ICG organized by US Dept. of State and UCAR held in Boulder CO, November 2015

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

Development Steps

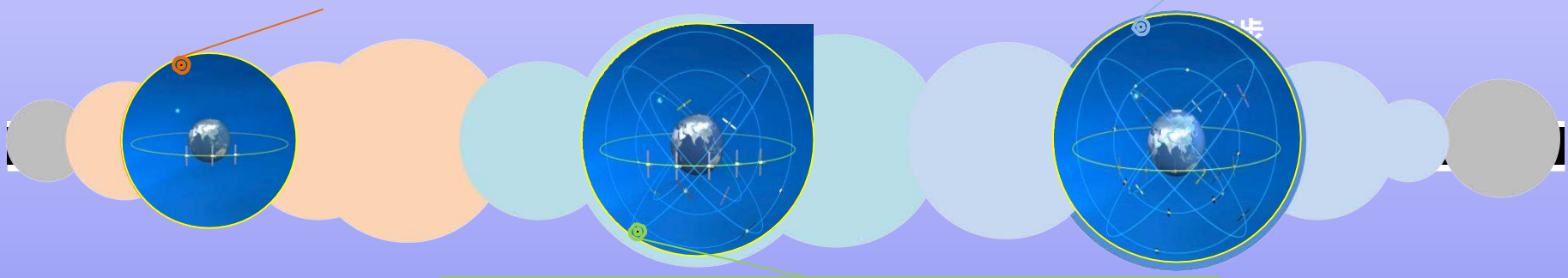
- BDS has been developing
  - **in line with the *three-step* roadmap**
  - **the thinking of *from regional to global, and from active to passive***
  - **forms a development path as *world-oriented, region- highlighted, with its unique features*.**

•The 1st step:

•1994~2000, provide regional active services

•The 3rd step:

•2013~2020, provide global passive services

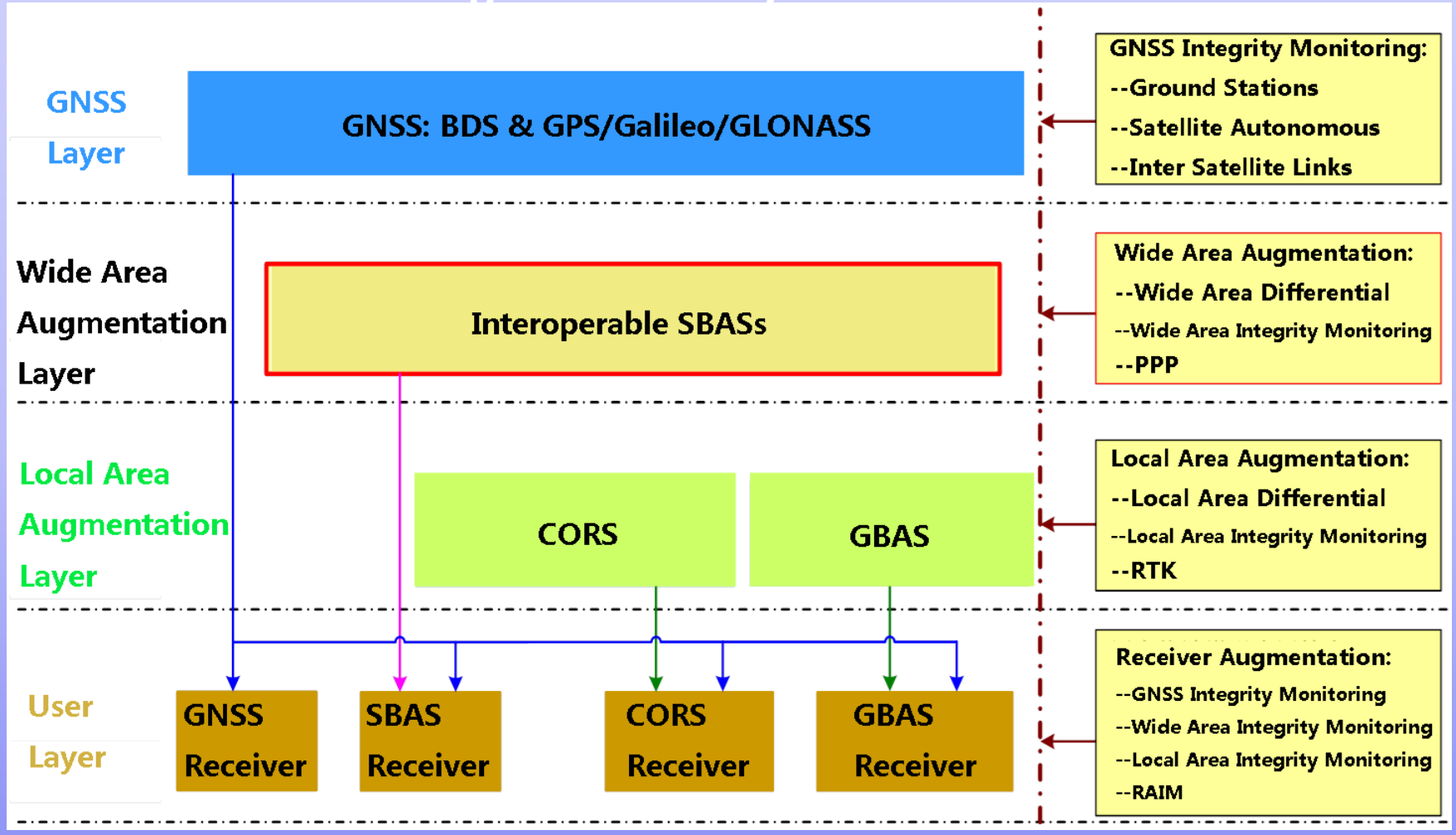


•The 2nd step:

•2004~2012, provide regional passive services

BDS - Design & Development Plan

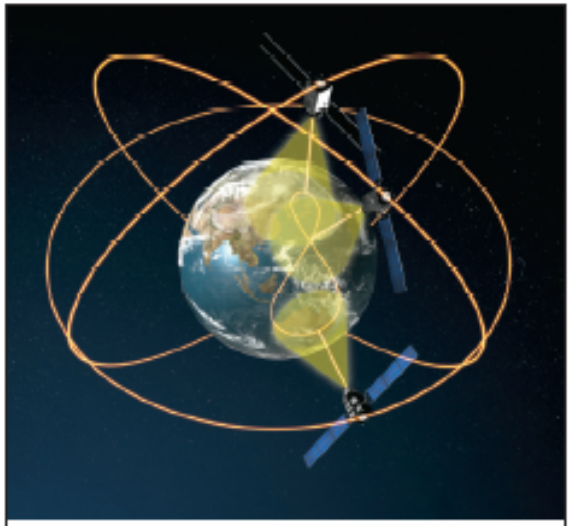
- BDS Augmentation System Architecture



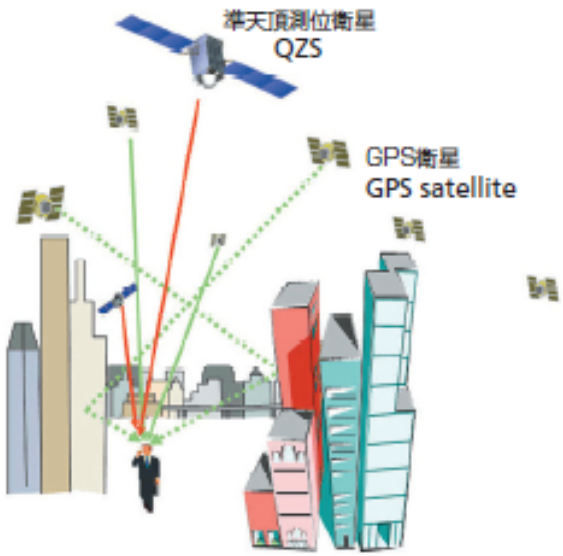
Quasi-Zenith Satellite System (QZSS)

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 L1C	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
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
- Seventh satellite launched 28 April 2016.
- Completed and operational in 2016

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

•http://www.irnssindia.co

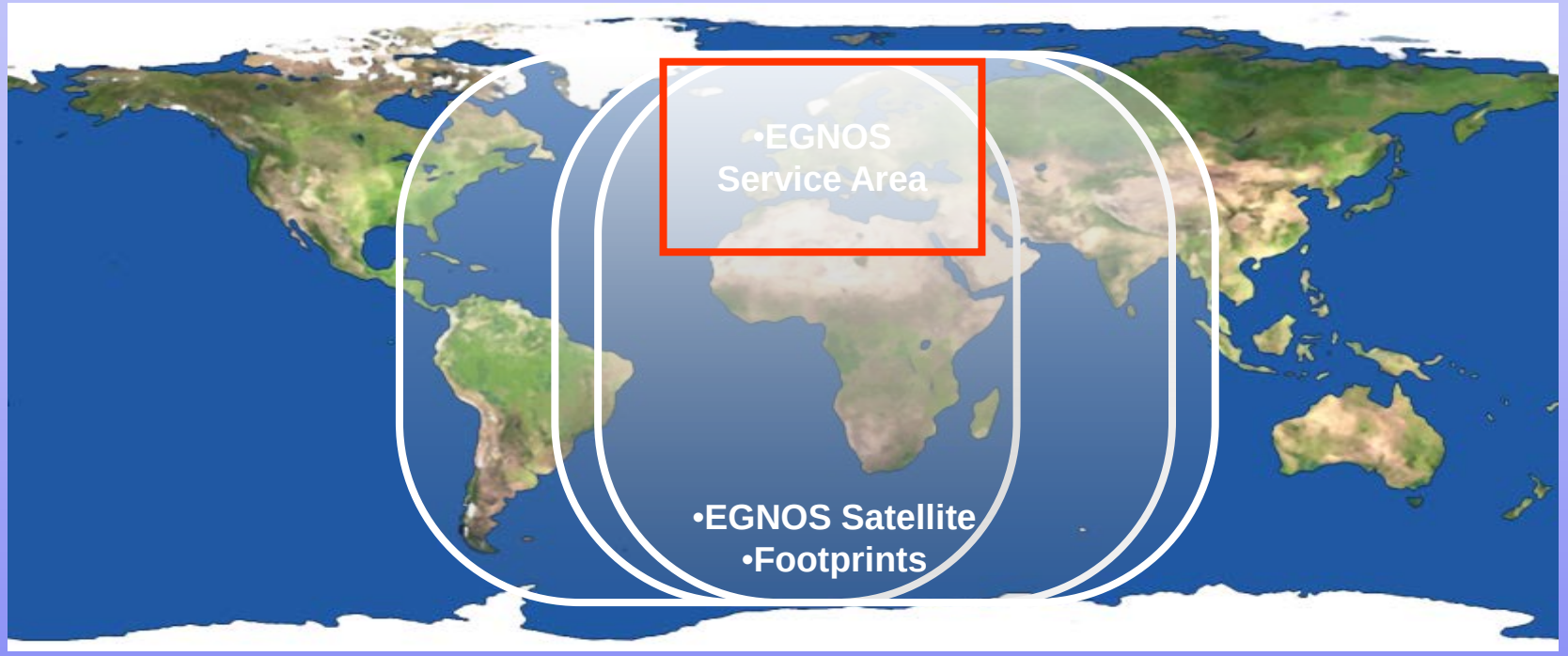
Indian GPS Aided Geo Augmented Navigation (GAGAN)

- 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