The Abdus Salam
International Centre
for Theoretical Physics

2458-8

Workshop on GNSS Data Application to Low Latitude Ionospheric Research

6 - 17 May 2013

Overview of the Global Navigation Satellite System (GNSS)

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

Overview of the Global Navigation Satellite System (GNSS)

Chris Hegarty

May 2013

MITRE

Global Navigation Satellite System (GNSS)

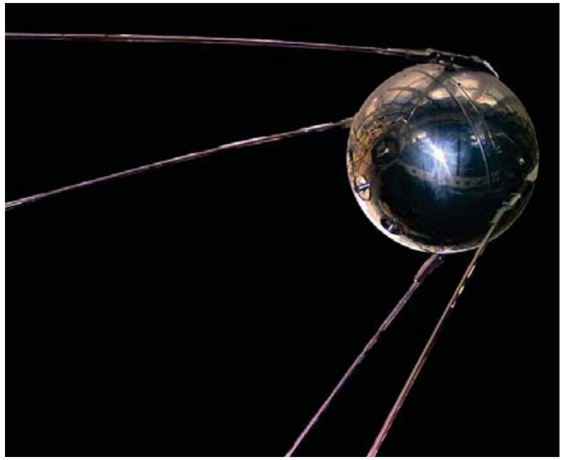
- Originally defined by the International Civil Aviation Organization (ICAO) as:

  "a worldwide position and time determination system that includes one or more satellite constellations, aircraft receivers and system integrity monitoring, augmented as necessary to support the required navigation performance for the intended operation"

- In popular usage today, "GNSS" is used interchangeably with "satellite navigation system"

A Historical Aside…

- Sputnik I - 4 October 1957
  - Inspiration for 1st satellite navigation system…
- U.S. Navy Navigation Satellite System (Transit)
  - Prototype satellite launched in September 1959
  - Operational from 1964 – 1996



Source: JHU APL.

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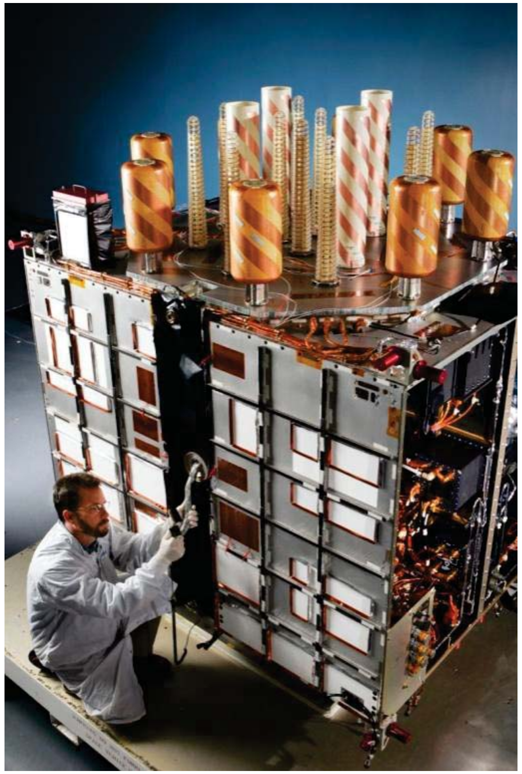
GNSS Constellations

- Global Positioning System (GPS)
- GLObal'naya NAvigatsionnaya Sputnikovaya Sistema (GLONASS)
- GALILEO
- BeiDou
- Quasi-Zenith Satellite System (QZSS)
- Indian Regional Navigation Satellite System (IRNSS)
- Satellite-based Augmentation System (SBAS)

Global Positioning System (GPS)

- U.S. satellite navigation system
  - Program began in early 1970's
  - First launch in 1978
  - Declared fully operational in 1995
- Nominal 24-satellite constellation
  - ~20,200 km altitude
  - 55 degree inclination
  - 6 orbital planes
  - Now 31 operational satellites



GPS Block IIR-M Satellite
Source: Lockheed-Martin.

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GPS Services

- Standard Positioning Service (SPS)
  - Available to all, free of direct user fees
  - Currently based upon one signal – the coarse/acquisition (C/A) code on L1 (1575.42 MHz)
  - Specified accuracy of 13 m, 95% (horizontal) and 22 m, 95% (vertical) (signal-in-space only)
- Precise Positioning Service (PPS)
  - Available only to authorized (military) users
  - L1 C/A-code plus precise (P) code signals on both L1 and L2 (1227.6 MHz)
    - P-code is normally encrypted into "Y"-code…
    - …but most survey-grade civilian receivers track

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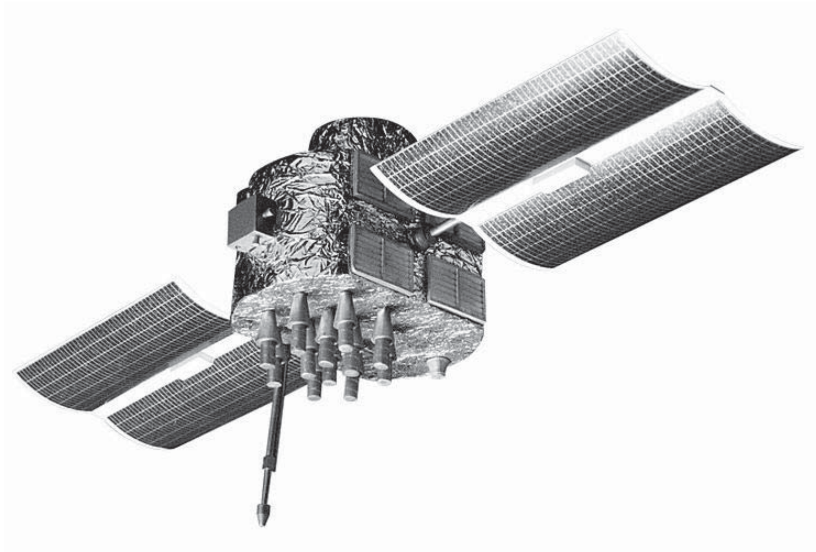
Block I GPS Satellites

- Developmental prototypes
- 11 total vehicles, built by Rockwell International
- Launched between 1978 and 1985
- Two cesium and two rubidium clocks each
- 5 year design life
  - None remain operational today



Block II/IIA GPS Satellites

- Initial and upgraded production satellites
- 28 total vehicles (9 Block II and 19 Block IIA), built by Rockwell International
- Launched between 1989 and 1997
- Two cesium and two rubidium clocks each
- Radiation hardened
- 7.5 year design life
  - 9 Block II/IIA are still in operation as of May 2013

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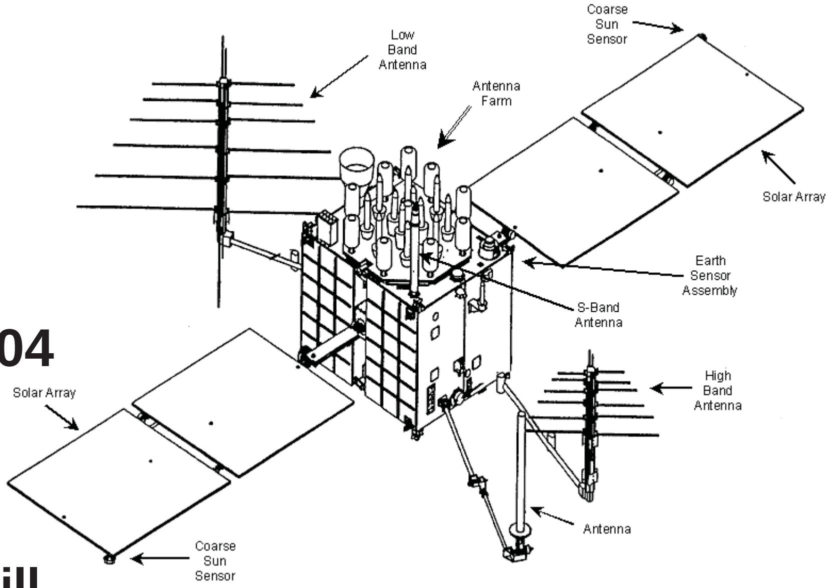
Block IIR GPS Satellites

- Replenishment satellites
- 21 total vehicles, built by Lockheed-Martin
  - IIR-1 lost on launch
  - Last 8 satellites have been modernized (IIR-M)
- 12 IIRs launched between 1997 and 2004
- Three rubidium clocks each
- 7.5 year design life
  - All 12 successfully-launched IIRs are still in operation as of May 2013



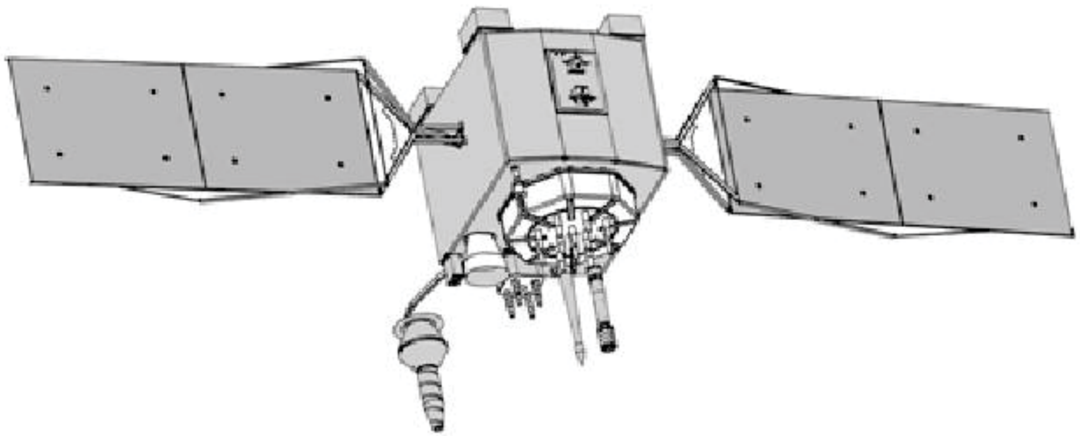
Source: Lockheed-Martin.

Block IIR-M GPS Satellites

- Modernized replenishment satellites
- 8 total vehicles, built by Lockheed-Martin
  - Last 8 satellites of 21-satellite IIR procurement
- First IIR-M launched in September 2005
  - Now: all have been launched; seven in operation
- Adds new civil and military signal capability
  - L2 Civil (L2C) signal
  - Military (M)-code signals on L1 and L2
  - Demonstration L5 package on IIR-M(20)

Block IIF GPS Satellites

- "Follow-on" satellites
- 12 total vehicles, being built by Boeing
- Three launched: May 2010, July 2011, and October 2012
  - Next: May 2013
- Adds new civil L5 signal at 1176.45 MHz
- Two rubidium and one cesium clock each
- 12 year design life



Source: Boeing.

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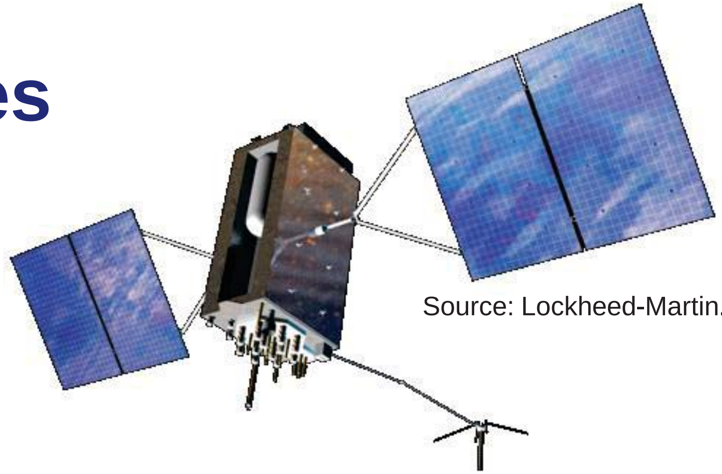
Block III GPS Satellites



Source: Lockheed-Martin.

- Next generation satellites
- Contract awarded to Lockheed Martin to build the first two Block III (IIIA) satellites in May 2008
  - With options for up to 10 additional IIIA vehicles
- First launch anticipated ~2015
- Potential Block III features (to be phased in incrementally):
  - New L1 civil (L1C) signal
  - “Spot beam” for military M-code signal
  - High-speed uplink/downlinks/crosslinks
  - Increased levels of accuracy, availability, reliability, and integrity

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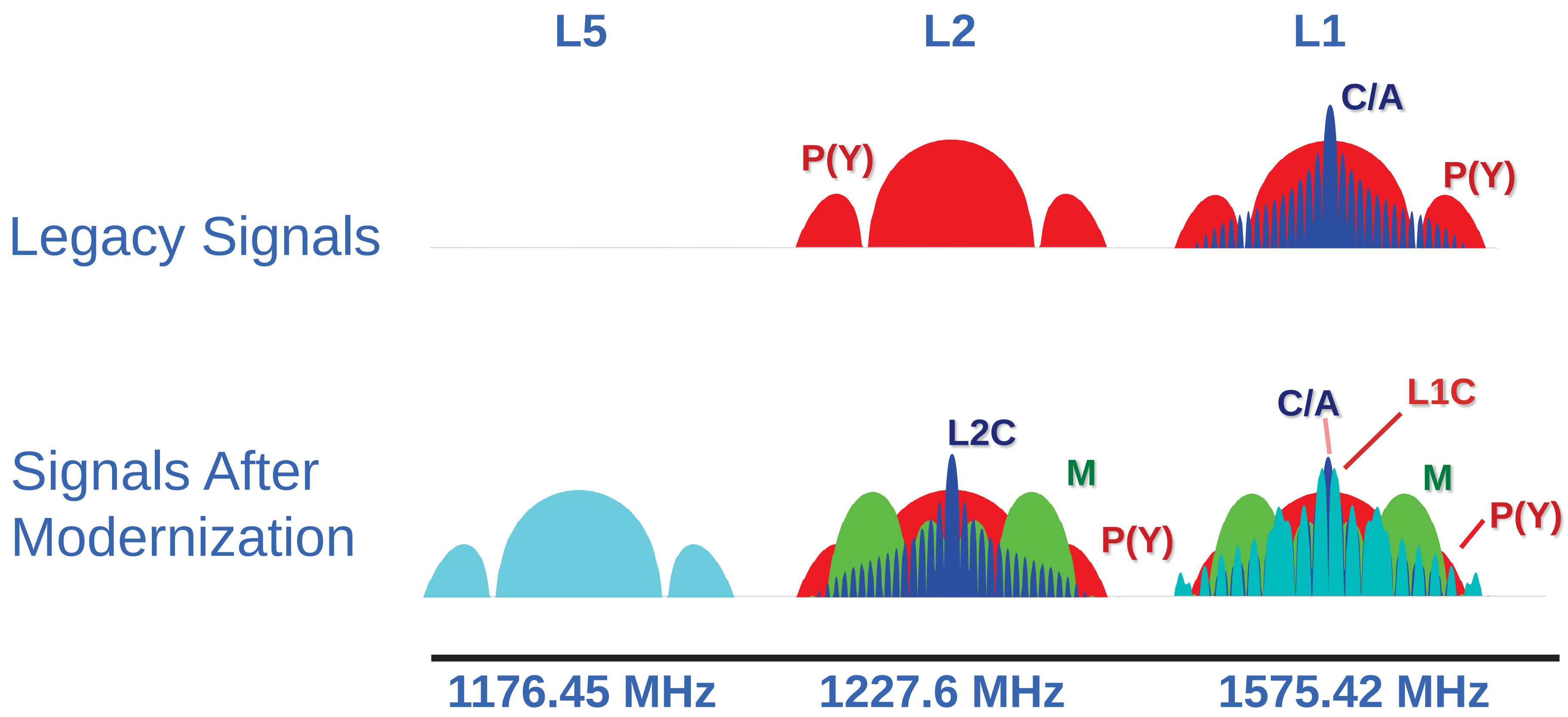
GPS Signal Evolution



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Features of Modernized GPS Signals

- Longer pseudorandom codes for open signals
  - Improves cross-correlation performance
- Dataless (pilot) components
  - Portion of signal energy devoted to component with no navigation data modulation
  - Enables more robust tracking
- Advanced modulation schemes
  - Binary offset carrier and variants
- Robust forward error correction
  - Convolution encoding, low-density parity check
- More precise navigation data

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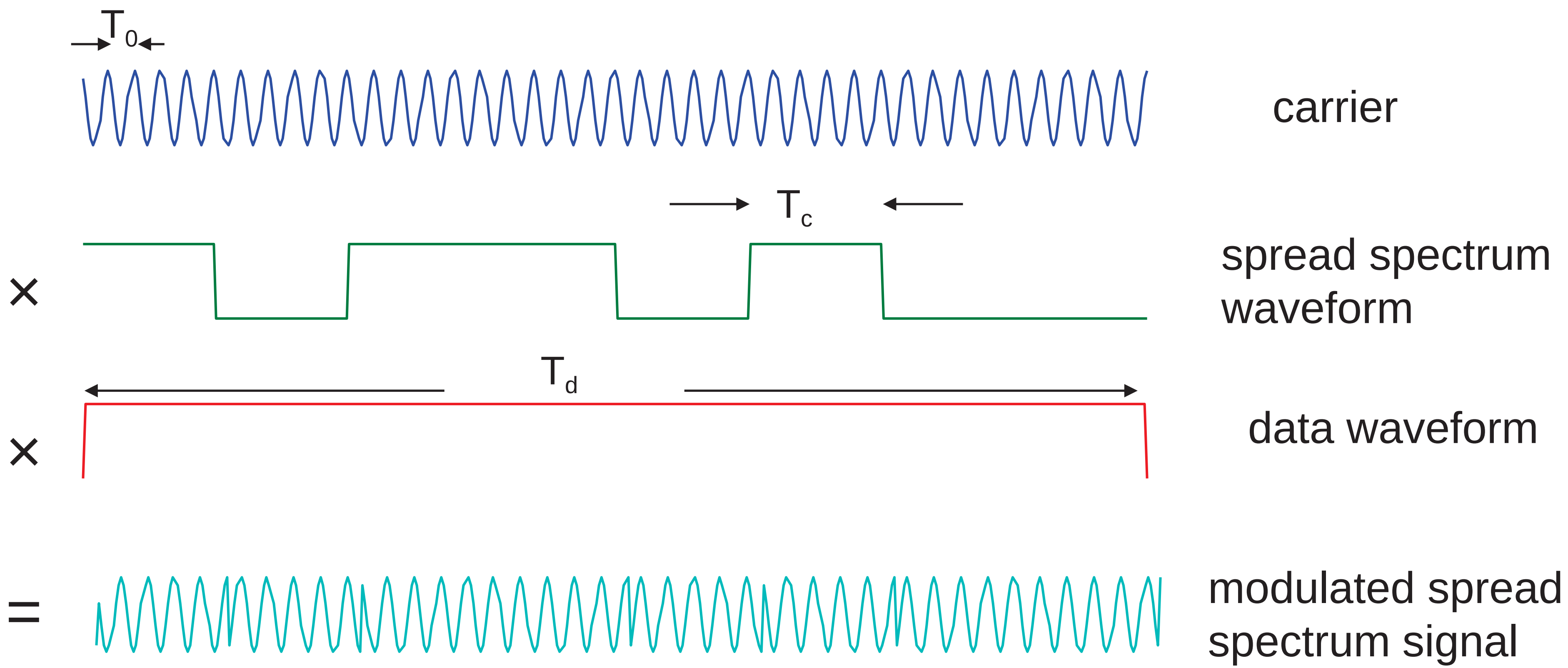
Direct Sequence Spread Spectrum

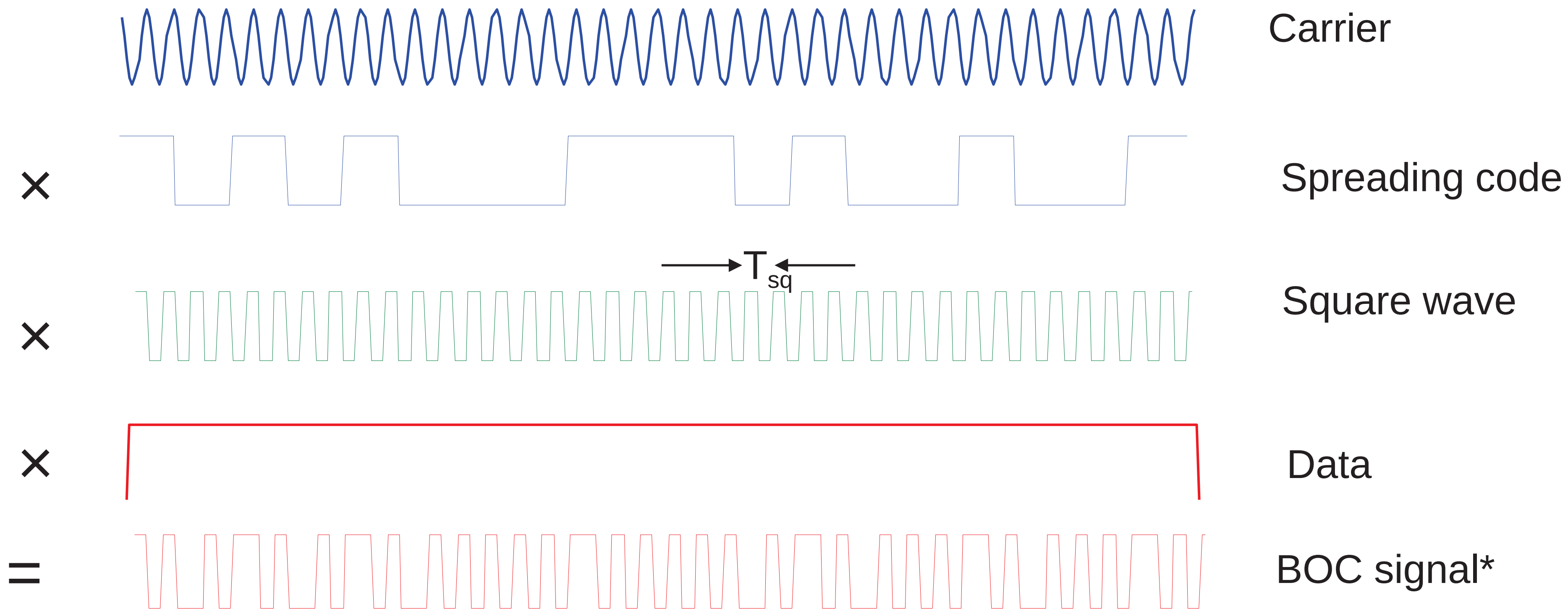


$R_c = 1/T_c$ = chipping rate (chips/s)

$R_d = 1/T_d$ = data rate (bits/s)

$f_0 = 1/T_0$ = carrier frequency (Hz)

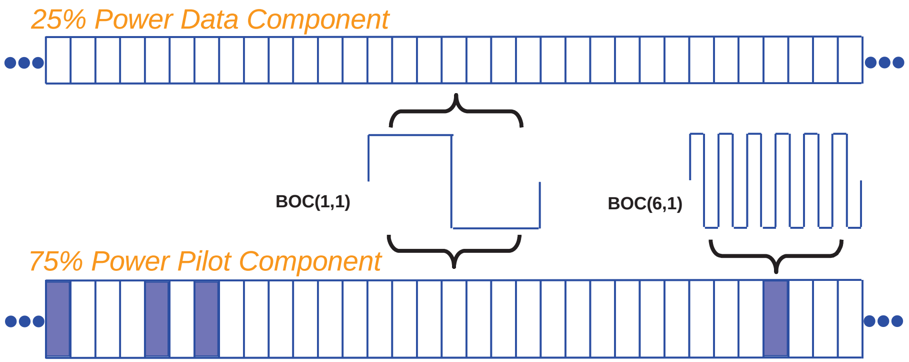
Binary Offset Carrier Modulation



$f_{sq} = 1/T_{sq}$ = subcarrier frequency (Hz)

*Shown at baseband, i.e., without carrier.

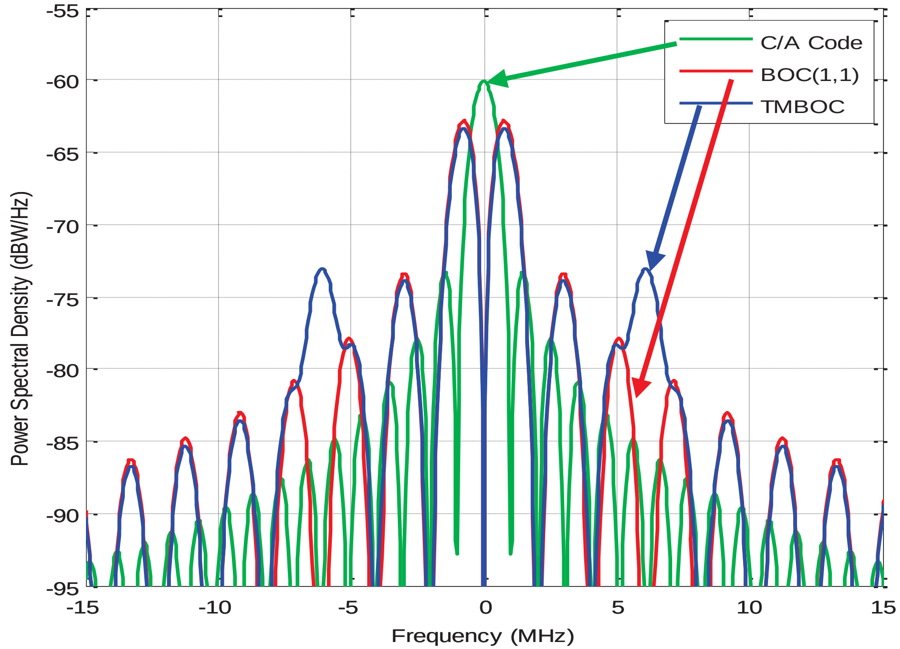
GPS L1C – Multiplexed BOC



$$\Phi_{Pilot}(f) = \frac{29}{33}\Phi_{BOC(1,1)}(f) + \frac{4}{33}\Phi_{BOC(6,1)}(f)$$

$$\Phi_{Data}(f) = \Phi_{BOC(1,1)}(f)$$

$$\Phi_{Signal}(f) = \frac{3}{4}\Phi_{Pilot}(f) + \frac{1}{4}\Phi_{Data}(f)$$
$$= \frac{10}{11}\Phi_{BOC(1,1)}(f) + \frac{1}{11}\Phi_{BOC(6,1)}(f)$$



Site of GPS L5 High-level Design Finalization

Photo courtesy of Dr. A.J. Van Dierendonck.

EUROPEAN COMMISSION
DIRECTORATE-GENERAL FOR ENERGY AND TRANSPORT

Director-General

Brussels, 1 8 JUIL. 2007
TREN/G5/MR/EA D(2007) 316635

Ms. Claudia A McMurray
Assistant Secretary for Oceans, Environment and Science
U.S. Department of State
Washington DC 20520
USA

Dear Ms McMurray,

In line with Article 11 paragraphs 5, 6 and 7 of the *Agreement on the promotion, provision and use of GALILEO and GPS satellite-based navigation systems and related applications* (the Agreement), I would like, on behalf of the European Community and its Member States, to notify you of our decision to change the Galileo Open Service, Safety of Life Service and Commercial Service signal from that described in the second bullet of paragraph (1) of the Annex of the Agreement to the Multiplex Binary Offset Carrier (MBOC) modulation. The description of the MBOC modulation is attached to this letter. I would also like to inform you that the European Community and its Member States would welcome the United States changing concurrently its signal structure from that described in the last sentence of the third bullet of paragraph (1) of the Annex to the MBOC modulation.

ours sincerely,

Matthias Ruete

GALILEO

United States Department of State

Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs

Washington, D.C. 20520

JUL 2 5 2007

Dear Mr. Ruete:

Thank you for your letters dated June 22 and July 18, 2007, regarding the adoption of the Multiplex Binary Offset Carrier (MBOC) modulation for certain Galileo signal structures. Your July 18 letter specifically notifies the United States, in accordance with Article 11, paragraphs 5, 6, and 7 of the *Agreement on the Promotion, Provision and Use of GALILEO and GPS Satellite-Based Navigation Systems and Related Applications* ("*Agreement*"), of the European Commission's decision to change the signal structures specified in bullet two of paragraph (1) of the Annex to the *Agreement.*

On behalf of the United States of America, and in accordance with the language of Article 11 paragraph 6 of the *Agreement*, I am pleased to inform the European Community and its Member States 1) that the United States will not oppose the adoption and implementation of the alternative signal structure specified in your notification; and 2) that, as a result of the close cooperation and collaboration fostered by the parties in Working Group A on radio frequency compatibility and interoperability for civil satellite-based navigation and timing services, the United States has decided to change its signal structure from that described in the last sentence of the third bullet of paragraph (1) of the Annex the aforementioned *Agreement* to the MBOC modulation (see Enclosure).

We are very happy about the progress we have made in this area and look forward to continuing our mutually beneficial cooperation.

Sincerely,

Reno L. Harnish, Acting

NAVSTAR GPS

Nominal GPS 24-Satellite Constellation

Slot	RAAN (deg)	Argument of Latitude (deg)	Slot	RAAN (deg)	Argument of Latitude (deg)
A1	272.847	268.126	D1	92.847	135.226
A2	272.847	161.786	D2	92.847	265.446
A3	272.847	11.676	D3	92.847	35.136
A4	272.847	41.806	D4	92.847	167.356
B1	332.847	80.956	E1	152.847	197.046
B2	332.847	173.336	E2	152.847	302.596
B3	332.847	309.976	E3	152.847	66.066
B4	332.847	204.376	E4	152.847	333.686
C1	32.847	111.876	F1	212.847	238.886
C2	32.847	11.796	F2	212.847	345.226
C3	32.847	339.666	F3	212.847	105.206
C4	32.847	241.556	F4	212.847	135.346

Defined Epoch: 0000Z, 1 July 1993; Greenwich Hour Angle: 18 h 36 min 14.4 s referenced to FK5/J2000.00 coordinates

Semimajor axis = 26559.7 km, inclination = 55 deg, eccentricity = 0

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Expandable GPS 24-Slot Constellation Slot Assignments

Expandable Slot		RAAN	Argument of Latitude	GEC (GLAN)
B1 Expands To:	B1F	332.847°	94.916°	101.25°
	B1A	332.847°	66.356°	86.97°
D2 Expands To:	D2F	92.847°	282.676°	135.13°
	D2A	92.847°	257.976°	122.78°
F2 Expands To:	F2F	212.847°	0.456°	114.02°
	F2A	212.847°	334.016°	100.80°

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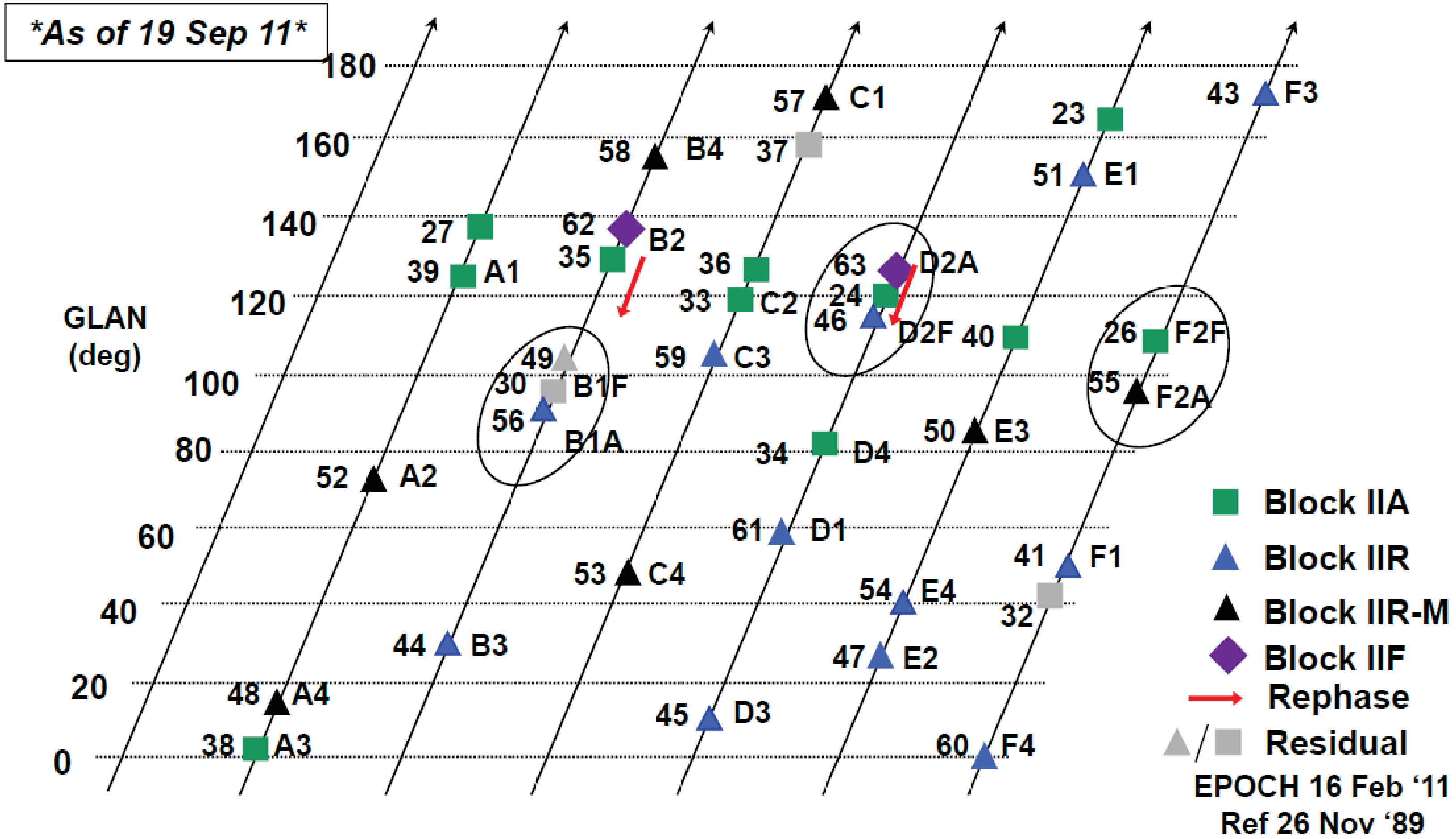
GPS Constellation Management

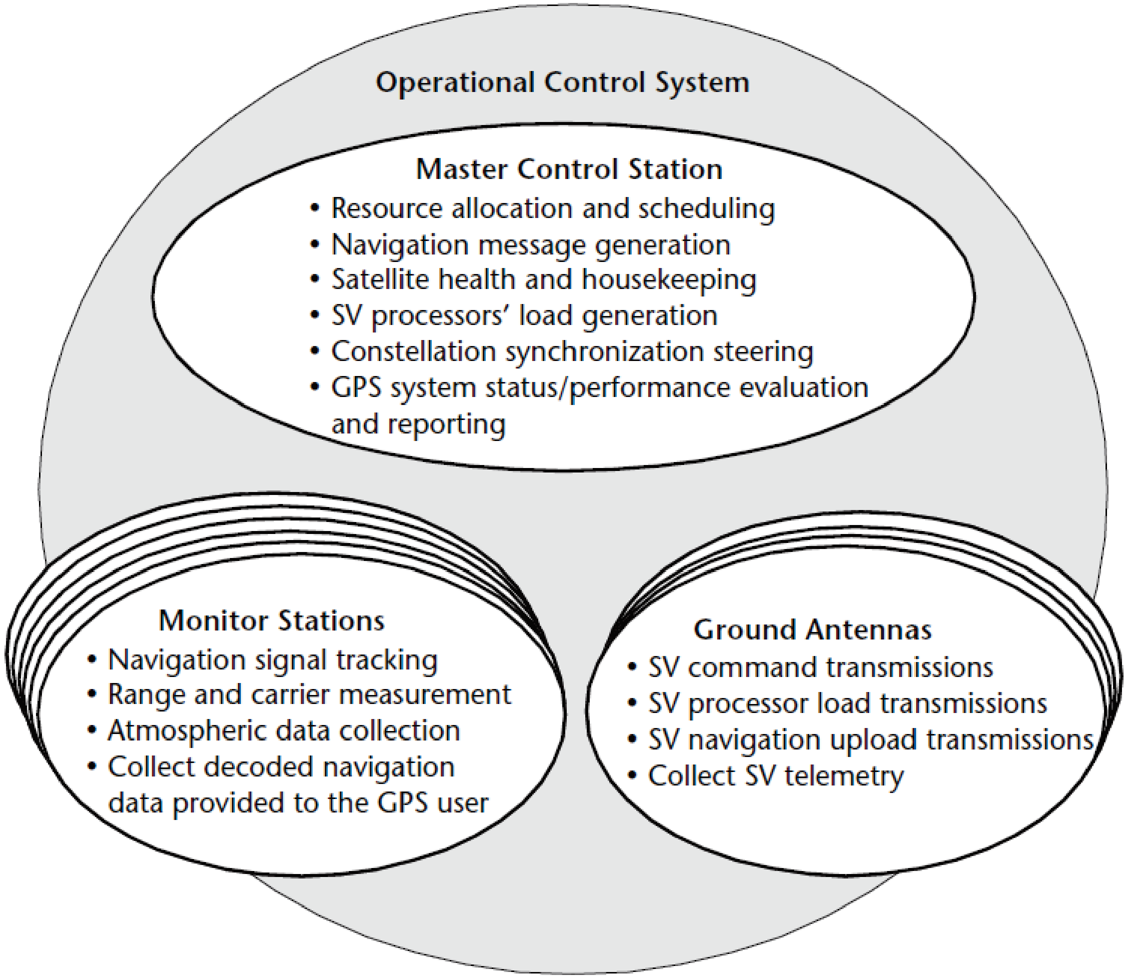


Source: United States Air Force, Civil GPS Services Interface Committee, September 2011.

GPS Constellation Design Features

- Asymmetric spacing in each plane
  - Selected based upon robustness considerations (e.g., performance of the constellation when satellite failures occur)
- Orbital period is ~one-half a sidereal day
  - Ground-tracks repeat ~once/day
- Orbital parameters selected in part by launch vehicle
  - Space shuttle was originally intended to be primary launch vehicle prior to the Challenger disaster

GPS Control Segment – Functional Overview



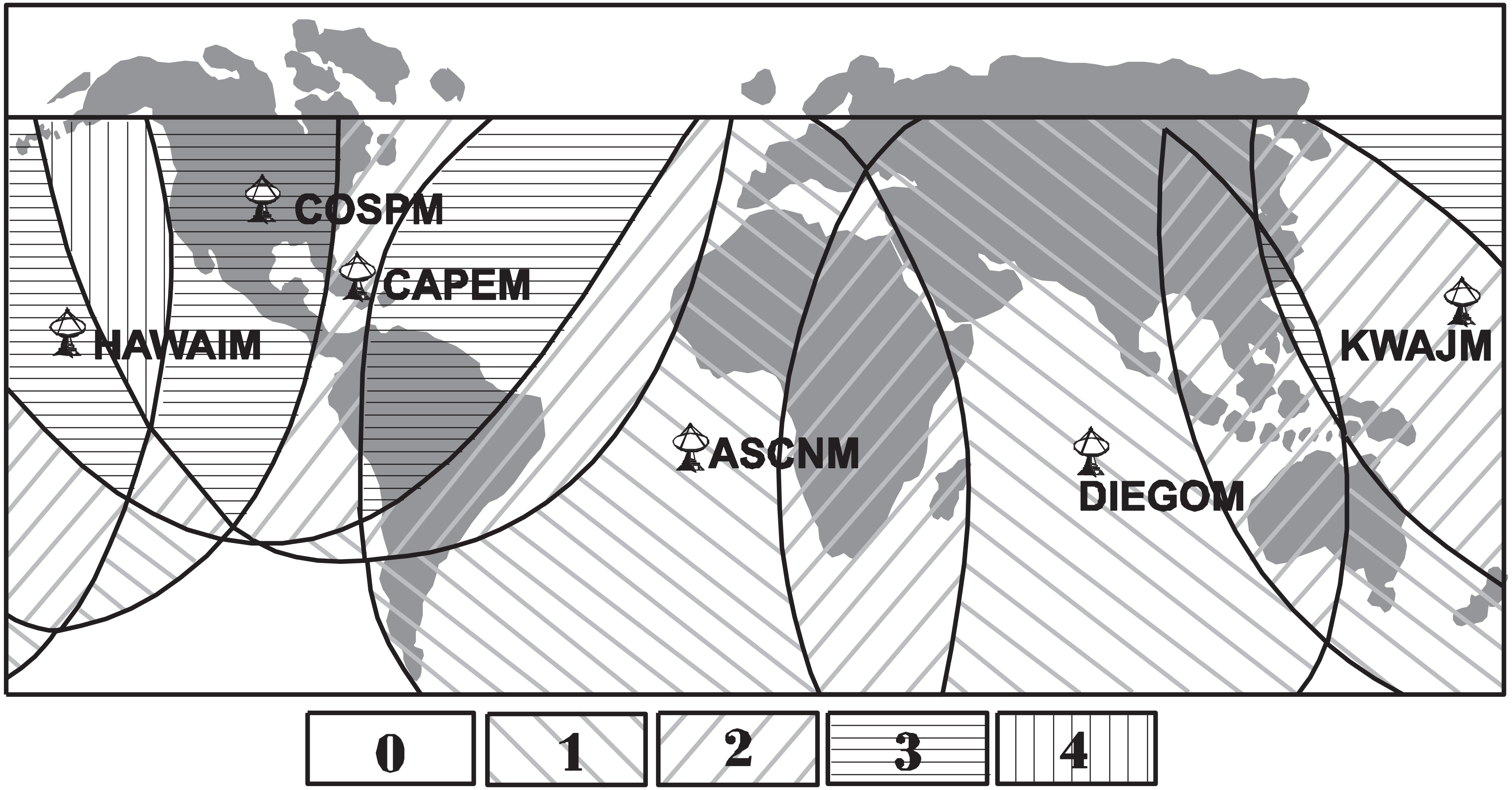
GPS Legacy Architecture and Architecture Evolution Plan (AEP)

- Legacy architecture (prior to September 2007)
  - MCS software was hosted on an IBM mainframe under Multiple Virtual Storage operating system
  - Since the 1980's the legacy architecture implemented a partitioned Kalman filter to estimate satellite positions and clock errors
    - Only up to six satellites and up to six monitor stations per partition
    - Limited accuracy
- Architecture Evolution Plan (AEP) (now in use)
  - Replaces mainframe with distributed Sun workstation configuration
  - Improved graphical user interface for GPS operators
  - Provides infrastructure for incremental control segment upgrades, e.g., to support new satellite blocks

GPS Legacy Control Segment

- ■ Master Control Station (MCS): **Satellite control, System operations**
- ■ Alternate Master Control Station: **Training, Back-up**
- ● Monitor Station (MS): **L-band; Collect range data, Monitor nav signals**
- ▲ Ground Antenna (GA): **S-band; Transmit data/commands, Collect telemetry**

Legacy Monitor Station Coverage



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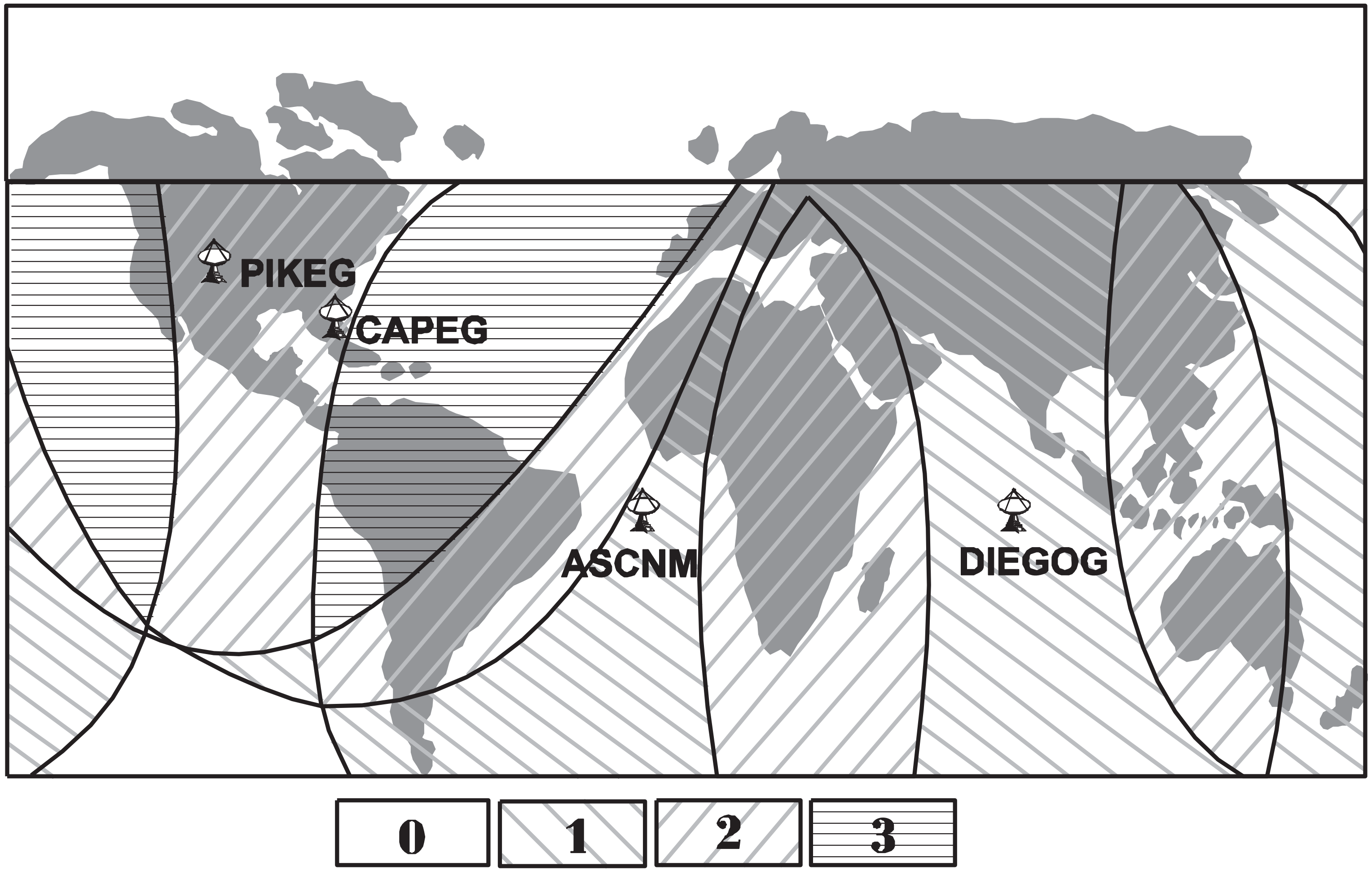
Ground Antenna Coverage



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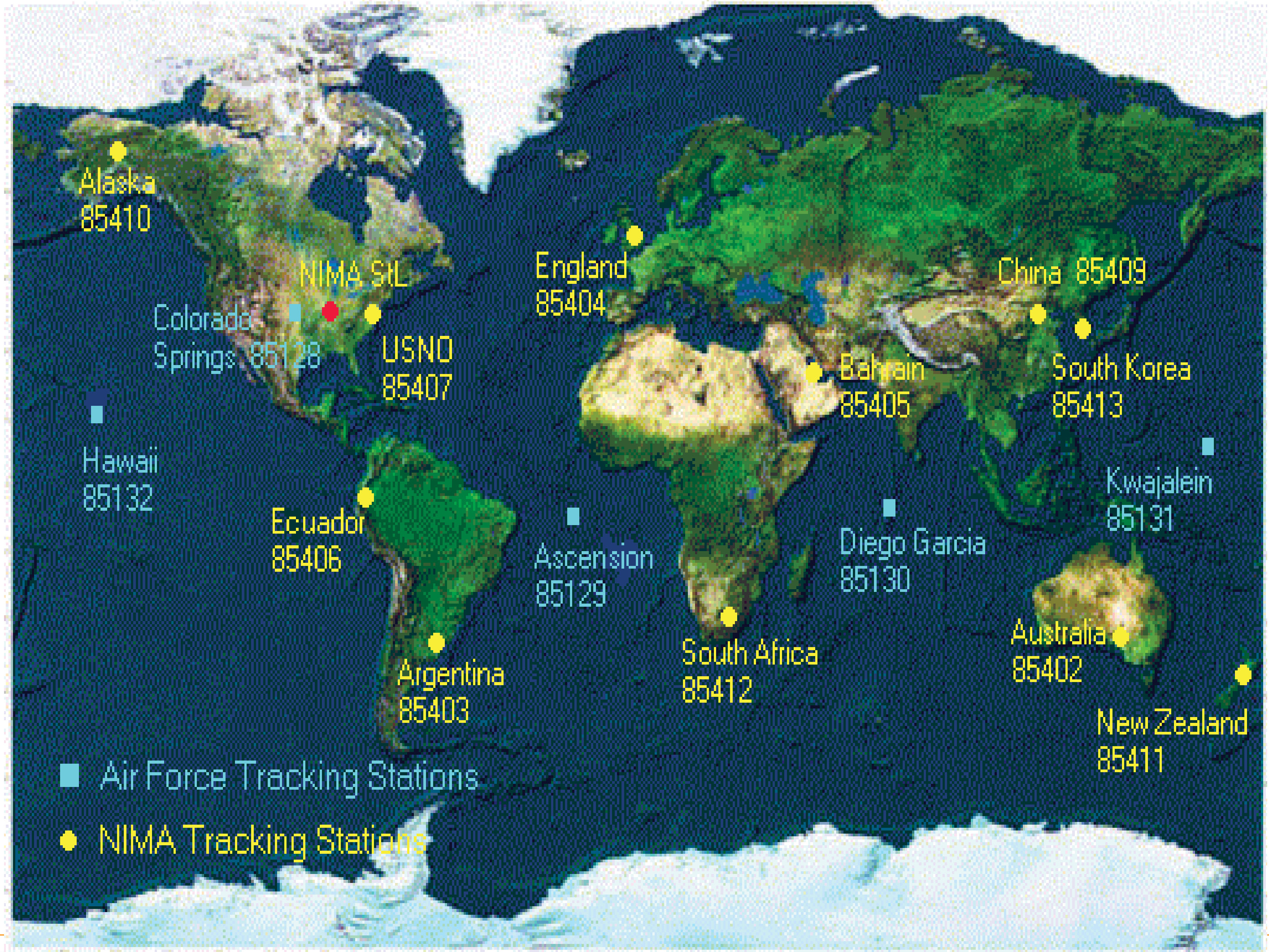
Legacy Accuracy Improvement Initiative (L-AII)

- Initiative began with legacy control segment
- Enabled up to 20 monitor stations and 32 satellites per Kalman filter partition
- National Geospatial-Intelligence Agency (NGA) monitor stations added to the existing AF monitor stations
  - Significantly improve system accuracy

Air Force and NGA Monitor Stations



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Current GPS Control Segment

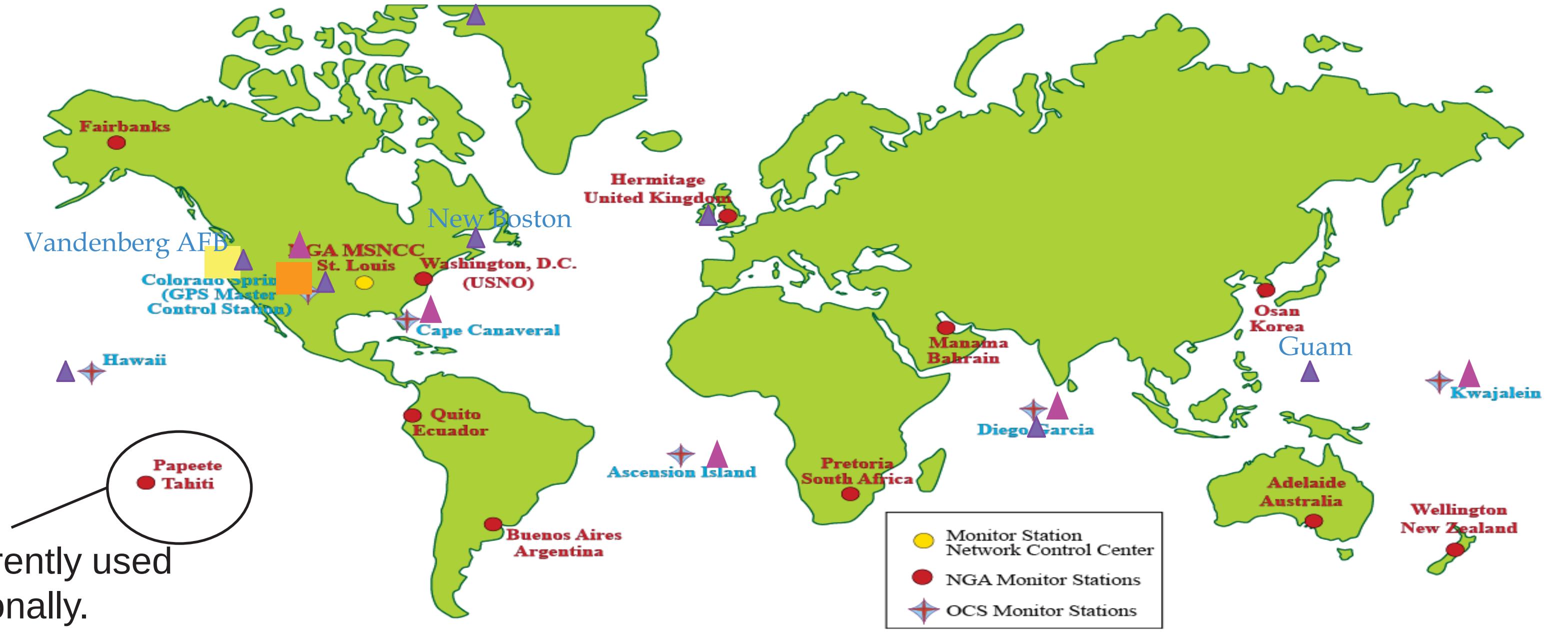
L-Band

S-Band

■ MCS at Schriever AFB, CO & Alternate MCS at VAFB

● 16 Monitor Stations
6 OCS + 10 NGA

▲ 12 Ground Antennas
4 GPS + 8 AFSCN



Not currently used operationally.

■	MCS Master Control Station Schriever AFB	■	AMCS Alternate MCS Vandenberg AFB

▲ GPS Ground Antennas

▲ AFSCN Remote Tracking Stations

Source: U.S. Air Force, Munich Satnav Summit, 2009.

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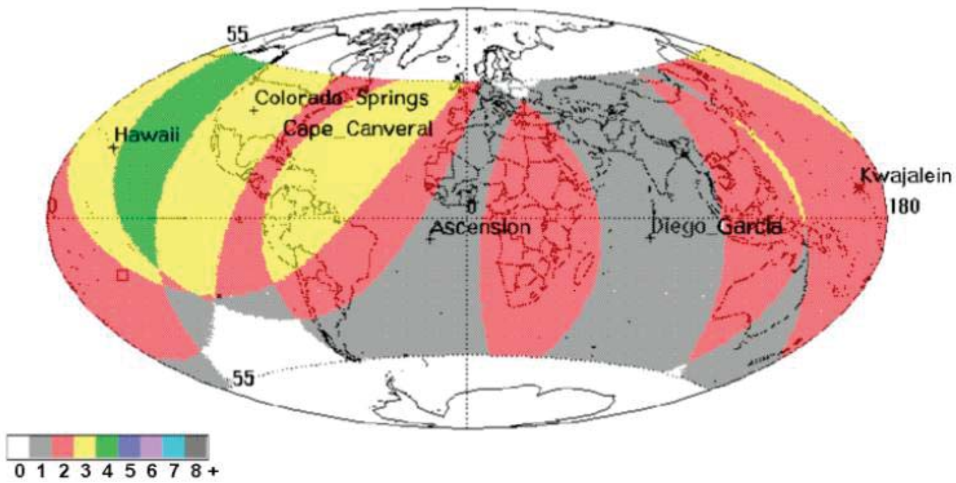
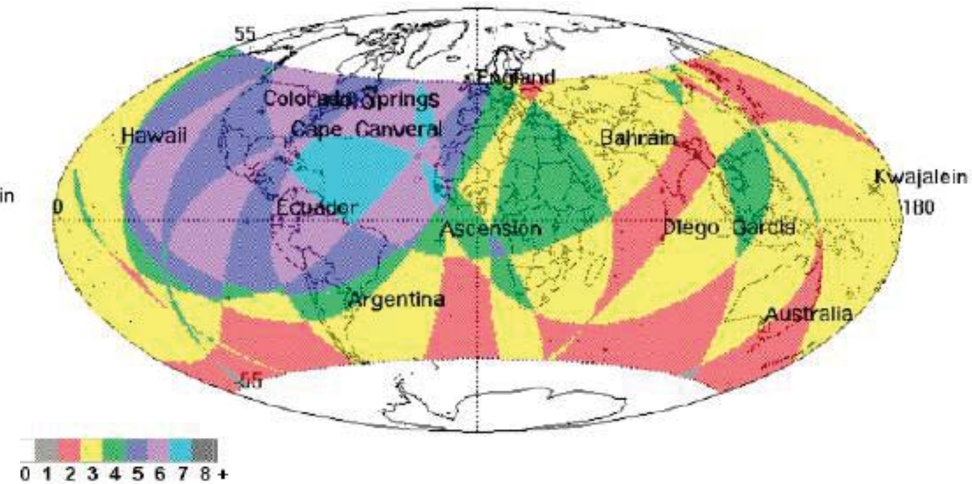
Coverage of AF and NGA Monitor Stations



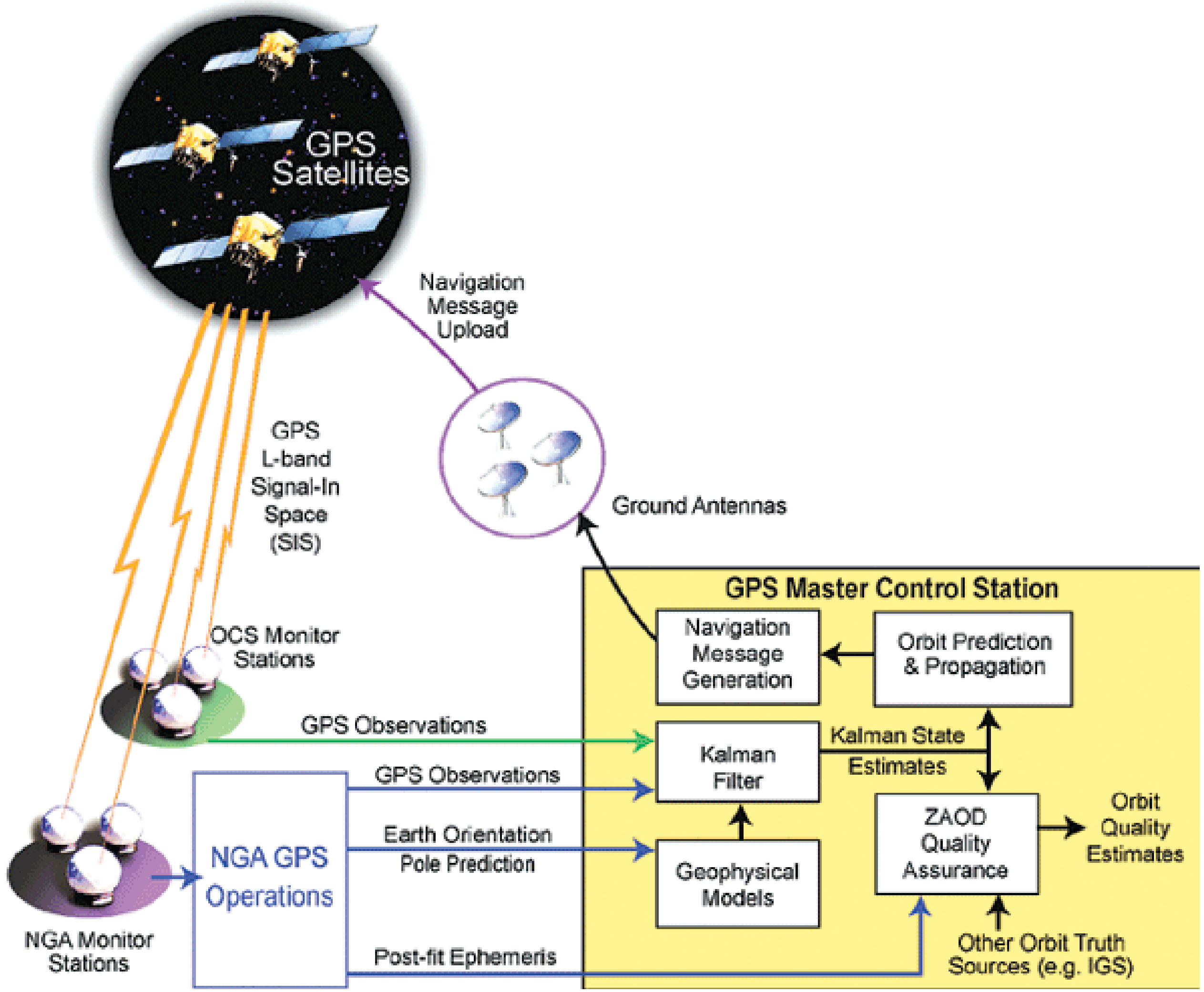
AF only



AF + NGA

Each plot shows the number of monitor stations that can see a satellite at a particular location (note that the white areas near the poles are locations where GPS satellites cannot go due to their 55 deg inclination orbits)

Control Segment – Data Flow



Source: Creel et al., “New, Improved GPS”, *GPS World*, March 2006.

MITRE

L-AII Model Improvements

Model	Baseline GPS Model	L-AII GPS Update Model	Date Implemented
Geopotential model	WGS84 8x8 gravitational harmonics	EGM 96 (12 x 12) gravitational harmonics	Aug 31, 2005
Station Tide Displacement	Solid Tide displacement accounting for lunar and solar vertical component only	IERS 1996, including vertical and horizontal components	Jun 8, 2005
Earth Orientation Parameters	No zonal or diurnal/semi-diurnal tidal com-pensation	Restoration of zonal tides and application of diurnal/semi-diurnal tidal corrections	Jun 25, 2005
Solar Radiation Pressure model	Rockwell Rock42 model for Block II/IIA and Lockheed Martin Lookup Table for Block IIR	JPL empirically-derived solar pressure model	Sep 21 – Dec 12, 2005
Troposphere Model	Hopfield/Black model	Neill/Saastamoinen model	Jun 8, 2005

Source: Creel et al., “New, Improved GPS”, *GPS World*, March 2006.

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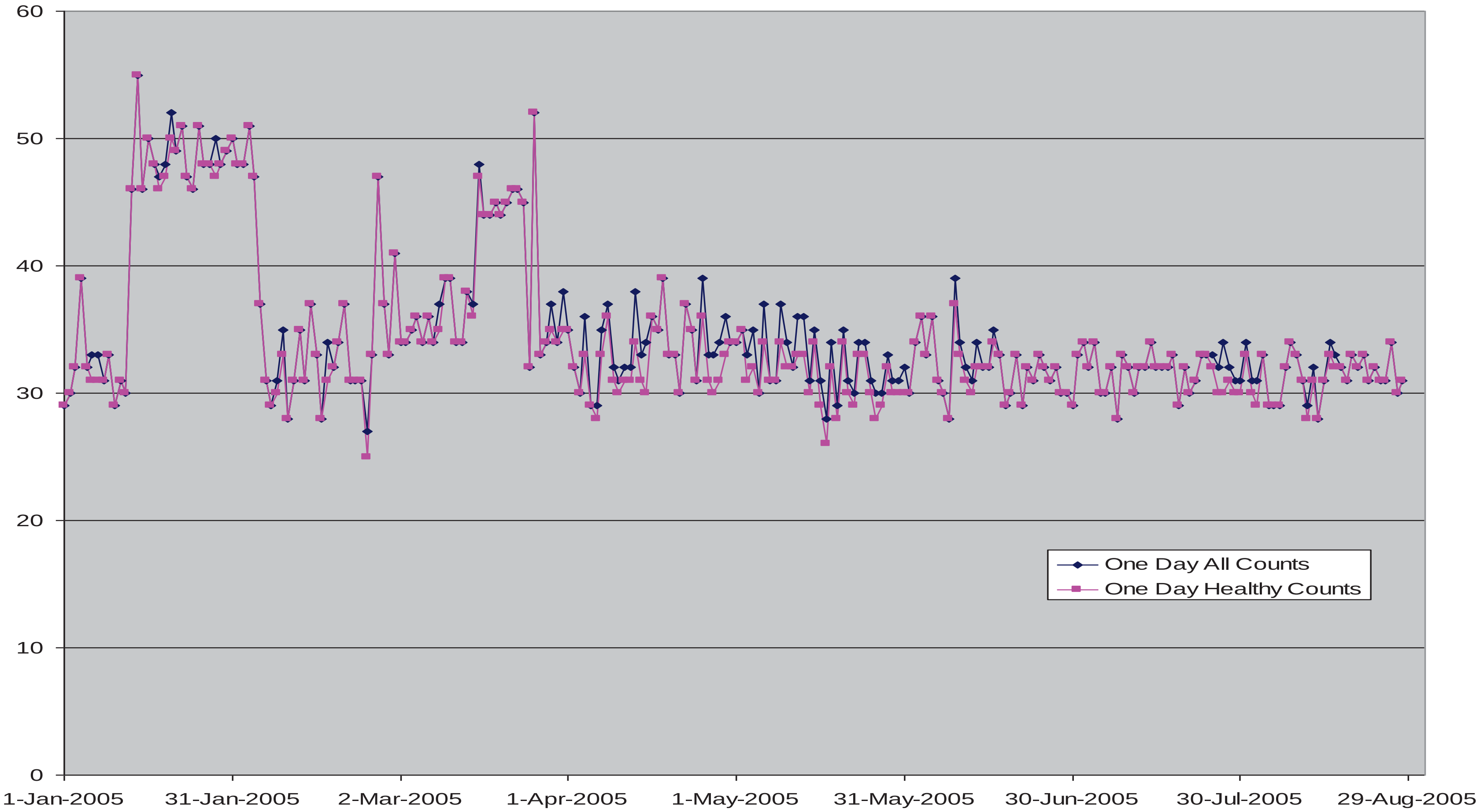
MCS Data Processing

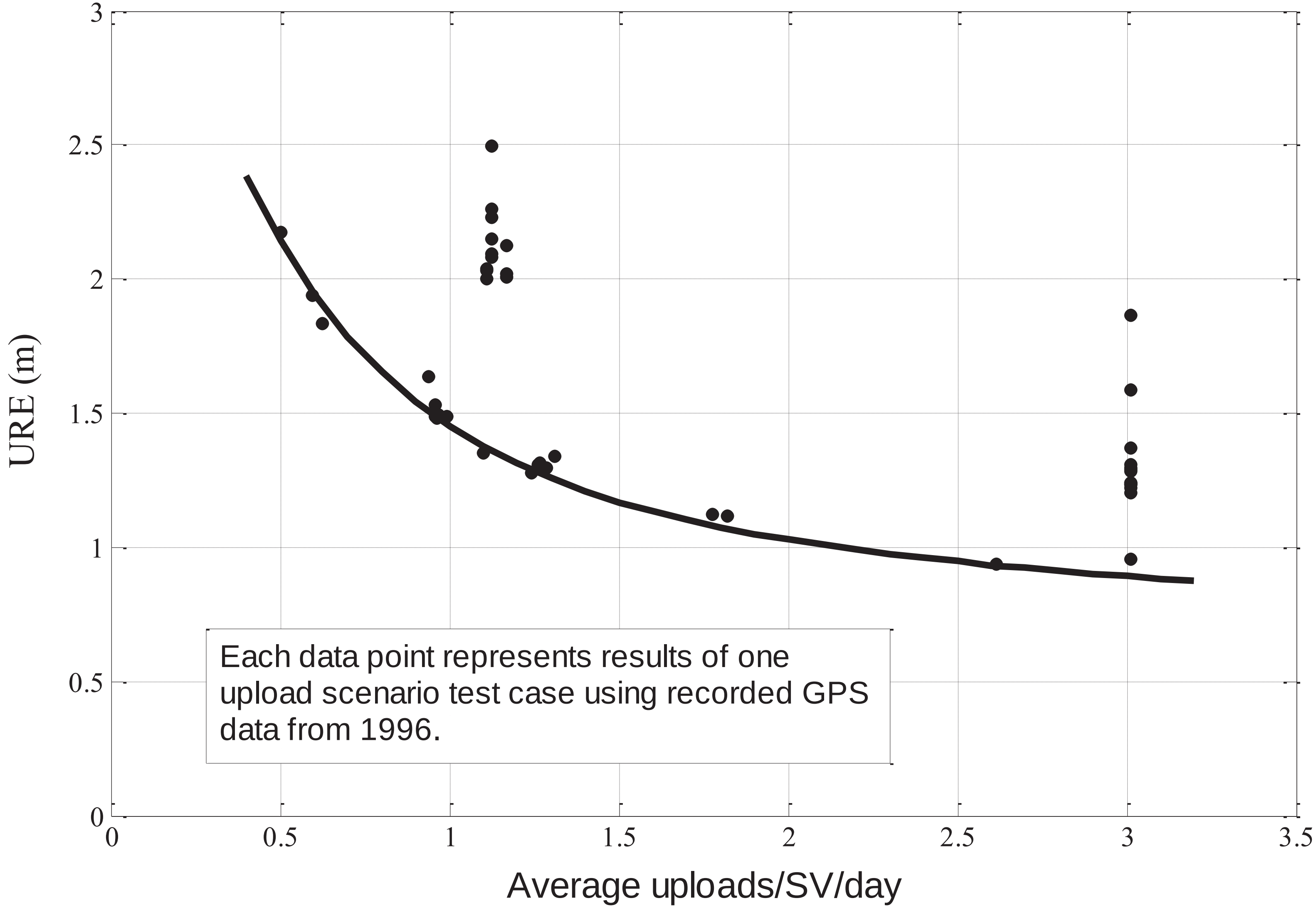
- Monitor stations measure pseudorange and carrier phase on L1 and L2 P(Y)-code signals
  - New measurements every 1.5 s
  - Data is smoothed to mitigate noise
- Kalman filter in MCS operates upon data from all monitor stations
  - Continually (15 min epochs) estimates satellite clocks and positions (and derivatives, tropospheric delays, solar radiation pressure levels, monitor station clocks, etc)
- MCS next predicts positions and clock errors for the satellites over the maximum period between satellite uploads
  - Curve fits are performed to obtain broadcast navigation data for nominal 4 hour fit intervals
  - Nominal transmission interval/set is 2 hours

Frequency of Daily Uploads



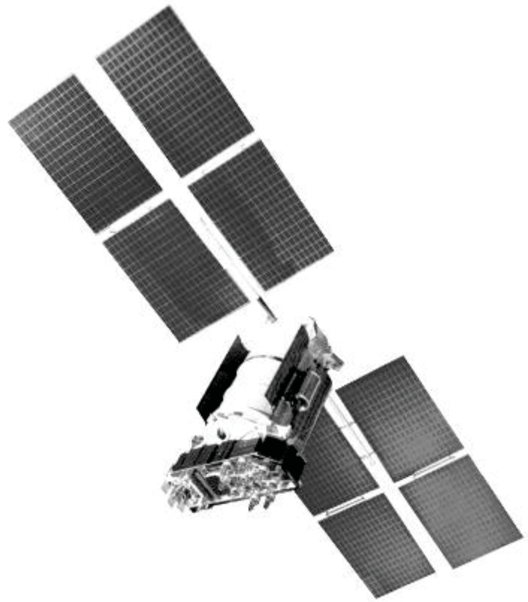
Daily uploads for each satellite is typical. More frequent uploads scheduled when necessary for poor-performing satellites.

System Range Accuracy vs Upload Frequency



GLObal'naya NAvigatsionnaya Sputnikovaya Sistema (GLONASS)

- Russian satellite navigation system
  - First launch in 1982
- Nominal 24-satellite constellation
  - 19,100 km altitude, 3 planes
  - Fully populated in 1995…
  - …but then deteriorated to as low as 7
- Now fully replenished – 24 operational satellites milestone reached in December 2011
- Frequency Division Multiple Access (FDMA)
  - Originally one open signal FDMA band, then two
  - Modernization plans are adding code division multiple access (CDMA) signals



Source: Russian Federation.

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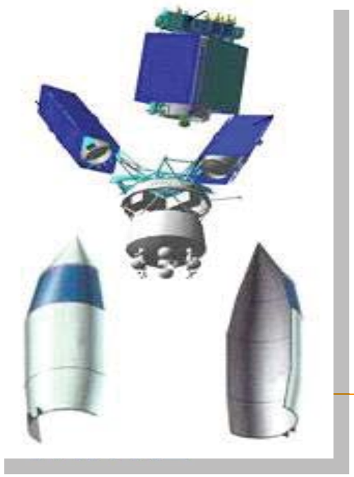
GLONASS Satellite

- **Guaranteed Life-time** — **3 years**
- **Satellite mass** — **1 415 kg**
- **Power supply** — **1 000 W**
- **Navigation payload**
  - **Mass** — **180 kg**
  - **Power consumption** — **600 W**
- **Clock stability (24 hours)** — **$5*10^{-13}$**
- **Attitude control accuracy** — **0.5 deg**
- **Solar panel pointing accuracy** — **5 deg**



Group launch by PROTON

Total launched 81 satellites
Actual life-time 4.5 years

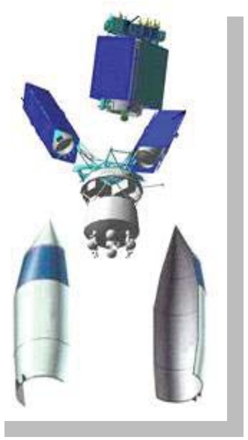
Source: Russian Federation.

GLONASS-M Satellite

• Guaranteed Life-time	7 years
• Satellite mass	1 415 kg
• Power supply	1 450 W
• Navigation payload	
– Mass	250 kg
– Power consumption	580 W
• Clock stability (24 hours)	$1*10^{-13}$
• Attitude control accuracy	0.5 deg
• Solar panel pointing accuracy	2 deg

GLONASS-M new features:

- Extended life-time
- L2 civil signal
- Improved clock stability
- Improved solar panel pointing
- Improved dynamic model, less level of unpredicted accelerations



Group launch by PROTON

Source: Russian Federation.

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GLONASS-K

- First unpressured GLONASS satellites
- 10-year design life
- GLONASS-K1 launched in Feb 2011
  - Adds test CDMA signal at 1202 MHz
- GLONASS-K2 and future –KM satellites will add additional CDMA signals

Source: Russian Federation.

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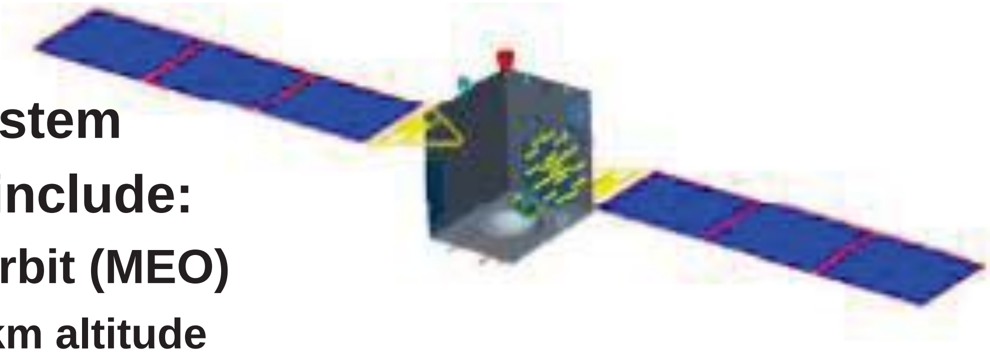
GALILEO

- European contribution to the GNSS
  – Jointly managed by European Commission (EC) and European Space Agency (ESA)
  – Program gained significant boost in March 2002 with release of ~$1.1B euro
- 27+ satellite constellation
  – 3-planes
  – 56 deg inclination
  – ~23,200 km altitude
- Two test satellites launched in 2005, 2008
  – No longer operating
- In-orbit validation (IOV) satellites: Oct 2011 (2), Oct 2012 (2)

Source: European Space Agency.

MITRE

BeiDou (COMPASS)



- Chinese satellite navigation system
- Final constellation planned to include:
  - 27 satellites in medium Earth orbit (MEO)
    - 55 degree inclination, ~21,500 km altitude
  - 5 satellites in geostationary orbit (GEO)
  - 3 - 5 satellites in inclined geosynchronous orbit (IGSO)
- Launches:
  - Four experimental GEOs: 2000 (2), 2003, 2007
  - MEOs: 2007, 2012 (4)
  - GEOs: 2009, 2010 (3), 2012 (2)
  - IGSOs: 2010 (2), 2011 (3)

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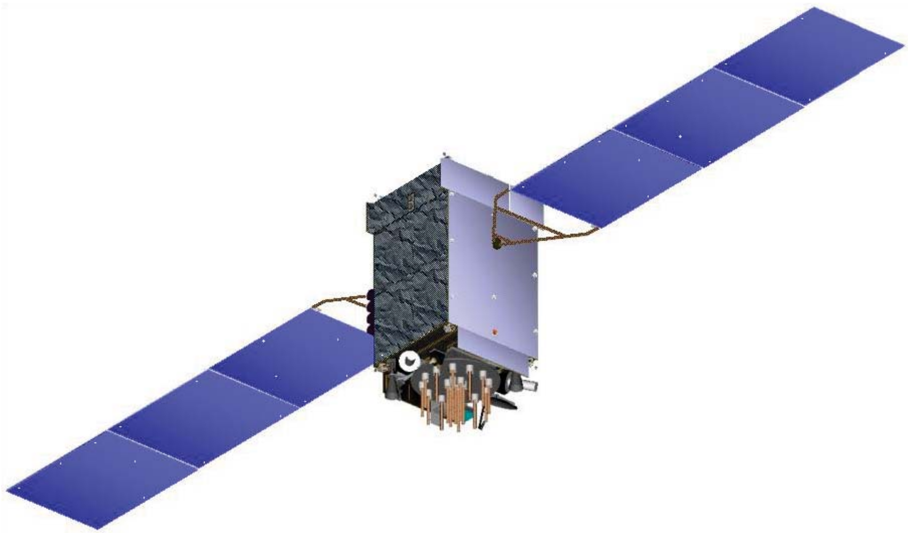
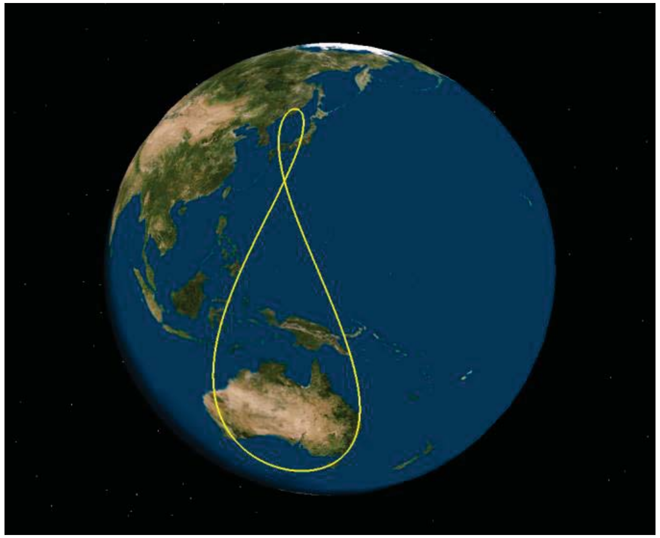
Quasi Zenith Satellite System (QZSS)

- Japanese system
- Plan calls for initially four satellites
  - Three highly elliptical ~36,000 km altitude orbits
  - One geostationary
  - Eventual growth to 7 satellites (design to-be-determined)
- First satellite launched September 2010





Source: Japan Aerospace Exploration Agency.

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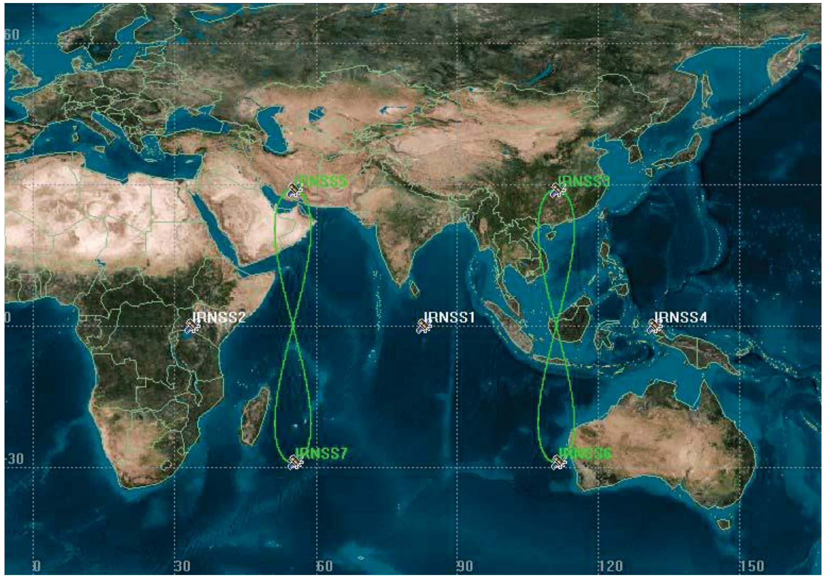
Indian Regional Navigation Satellite System (IRNSS)

- Indian regional system
- Final constellation planned to include:
  - 3 satellites in geostationary orbit (GEO)
  - 4 satellites in inclined GSO
- First launch planned ~ June 2013



Source: Indian Space Research Organization.

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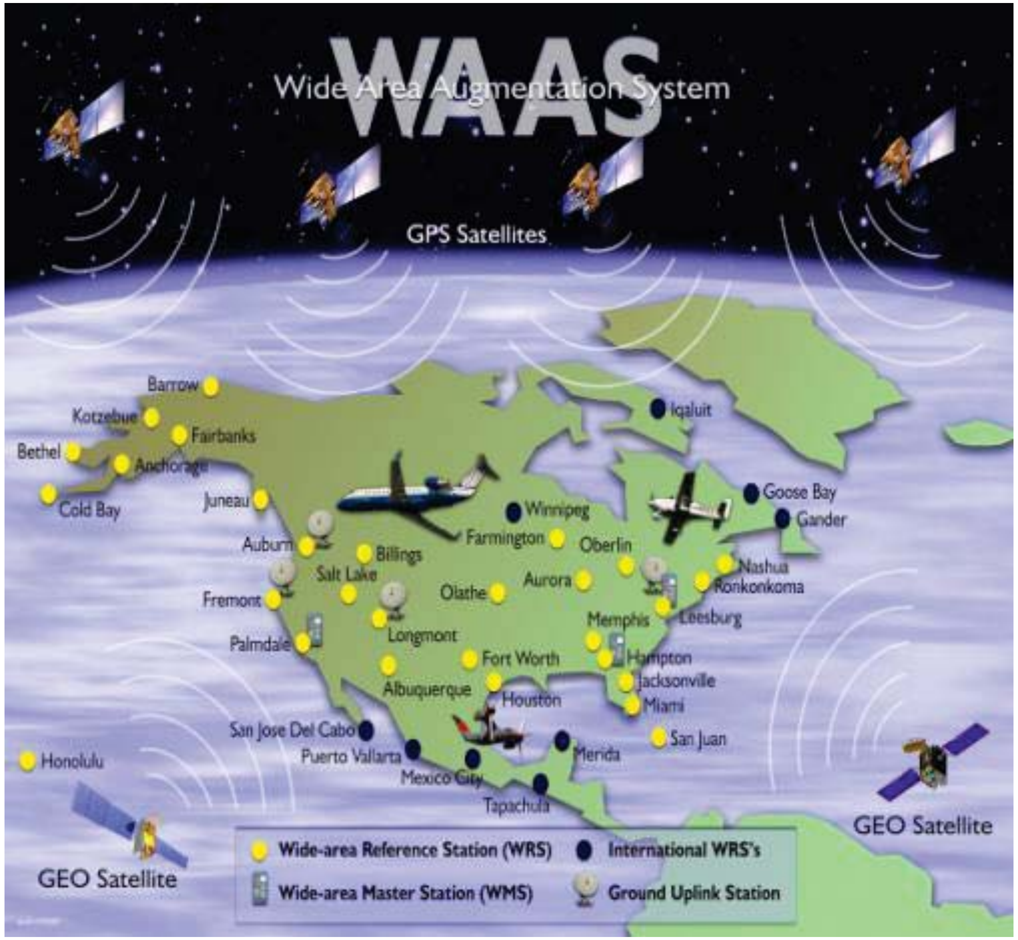
Wide Area Augmentation System (WAAS)



38 Reference Stations

3 Master Stations

6 Ground Earth Stations

3 Geostationary Satellite Links

2 Operational Control Centers

WAAS Paumalu, Hawaii Ground Earth Station

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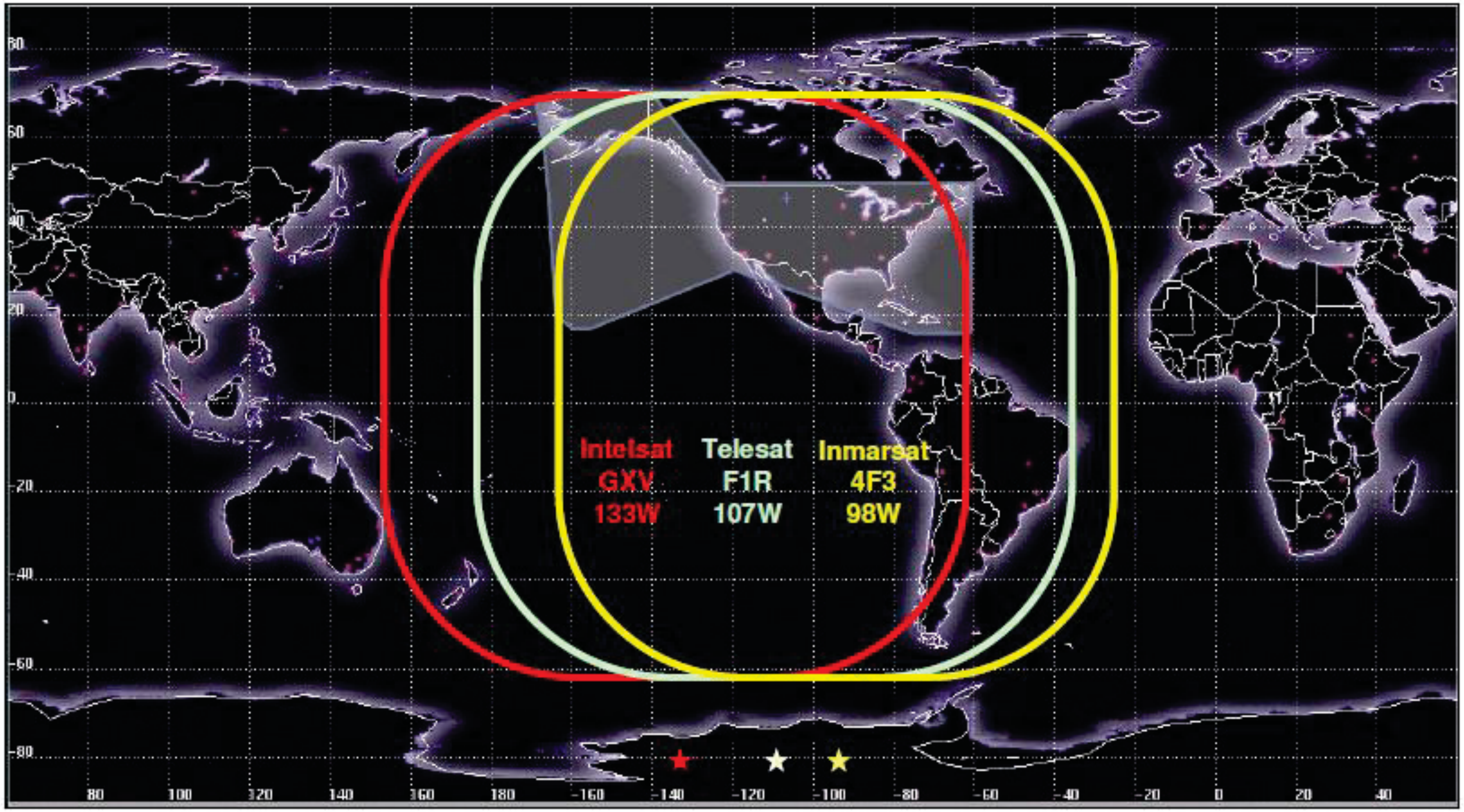
WAAS Coverage



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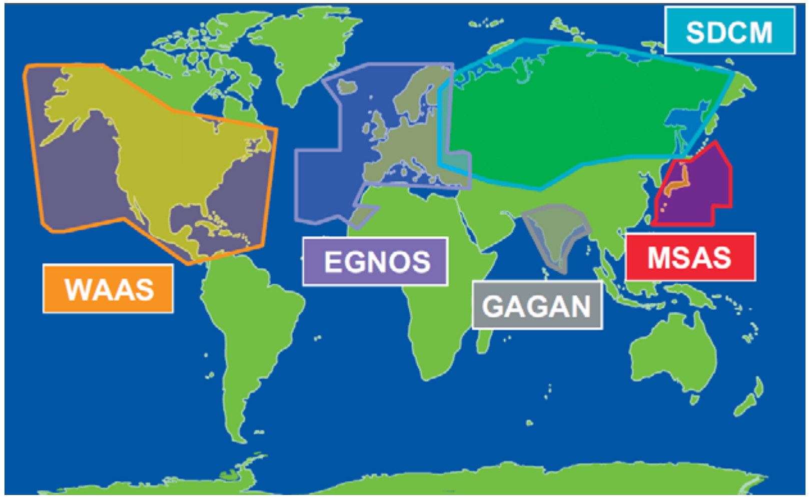
Other Satellite-based Augmentation Systems (SBAS)

- Europe: European Geostationary Navigation Overlay Service (EGNOS)
  - Operational - three satellites
- Japan: Multifunctional Transport Satellite (MTSAT)-based Augmentation System (MSAS)
  - Operational - two satellites
- India: GPS and GEO Augmented Navigation (GAGAN)
  - Not yet operational - 2 satellites in orbit
- Russia: System of Differential Correction and Monitoring (SDCM)
  - Not yet operational - 1 satellite in orbit



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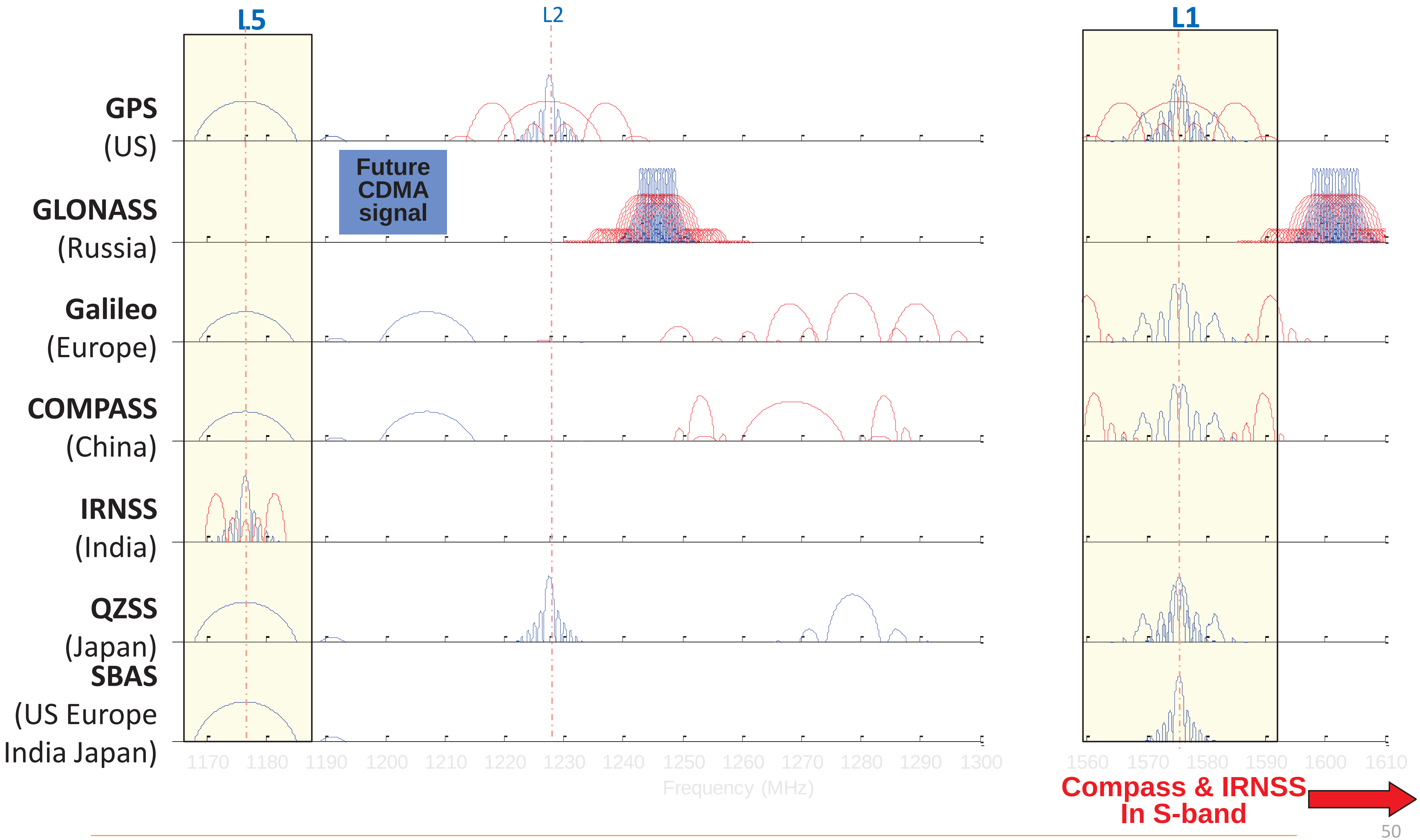
GNSS Signal Plans



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GNSS Summary

System	Satellites Now in Orbit			Satellites Planned		
	MEO	GEO	IGSO	MEO	GEO	IGSO
GPS	31	0	0	24+	0	0
GLONASS	24	0	0	24+	0	0
GALILEO	4	0	0	27+	0	0
COMPASS	5	6	5	27+	5	5
QZSS	0	0	1	0	3	4
IRNSS	0	0	0	0	3	4
SBAS	0	11	0	0	12+	0
TOTAL	**64**	**17**	**6**	**102+**	**33+**	**13**

- **GNSS now includes 87 satellites (plus associated ground networks)**
- **More than 150 satellites anticipated within a decade**

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