GNSS as Primary Time Source

WSTS 2021 TUTORIAL SESSION

March 24, 2021

Marc A. Weiss, Ph.D.
Marc Weiss Consulting LLC
marcweissconsulting@gmail.com

Two Messages About GNSS

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

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

The Family of Global Navigation Satellite Systems

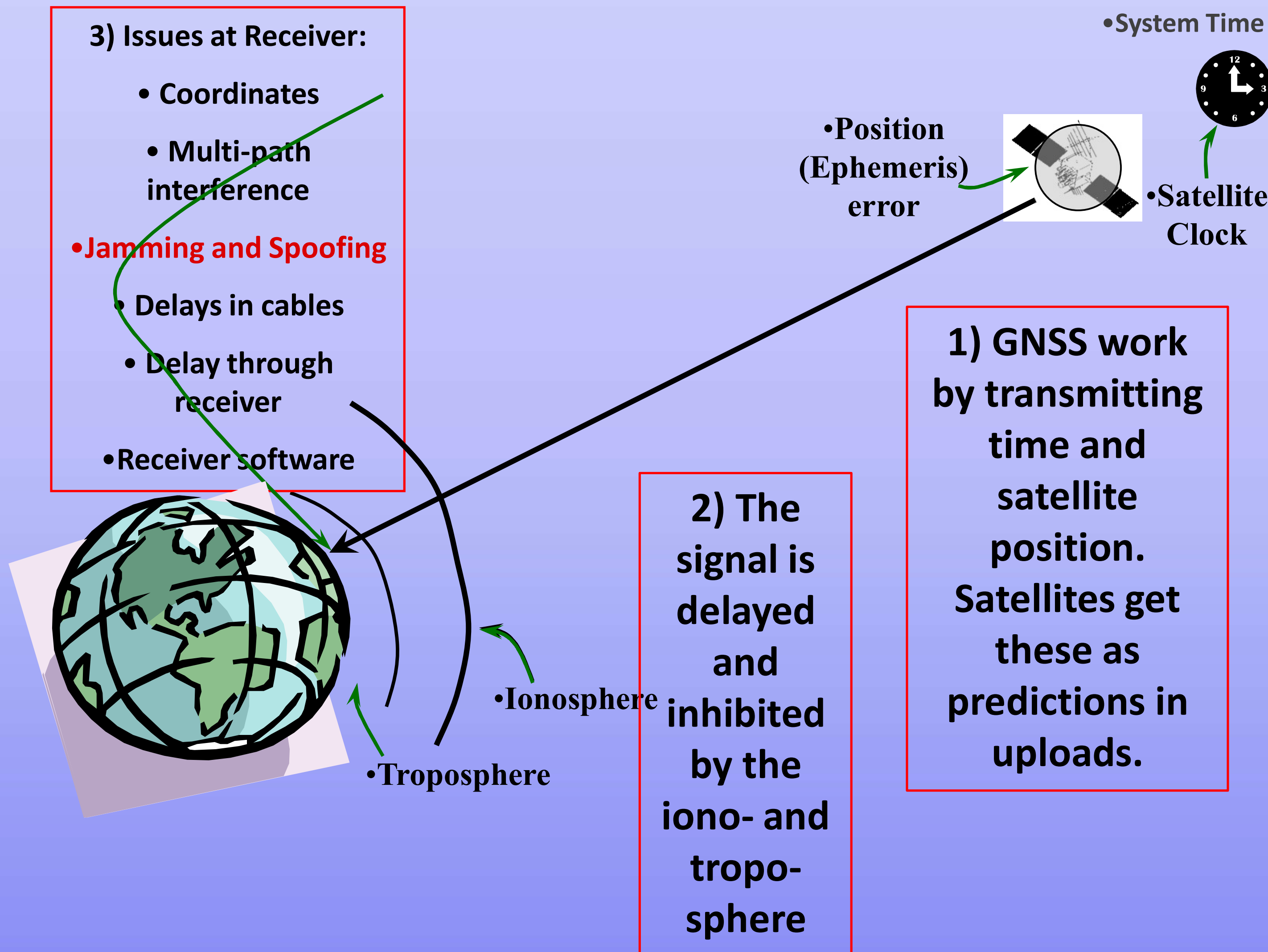
GPS	Galileo	GLONASS	Beidou/Compass
US	EU	Russia	China

Others are Regional Navigation Satellite Systems

GNSS: 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

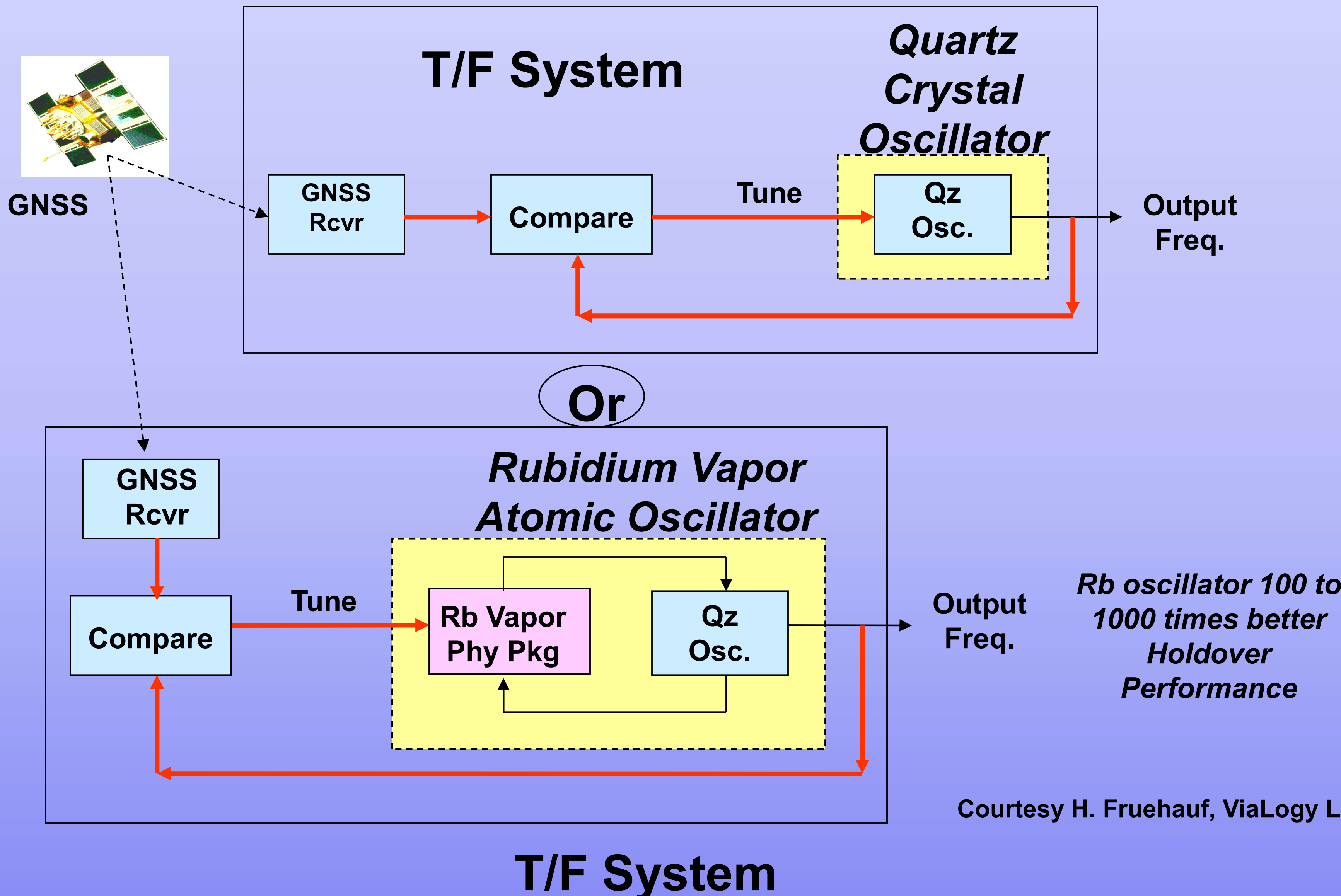
Time from GNSS:
Intentional and Unintentional Error Sources



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

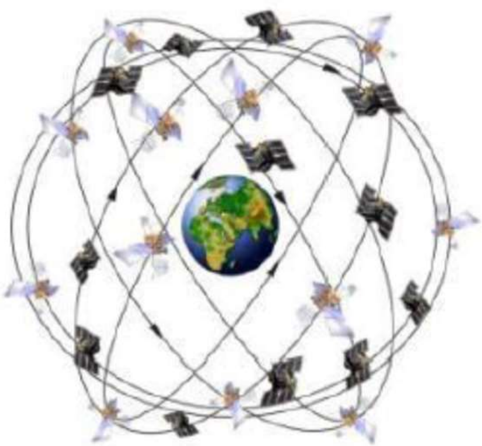
GNSS-aided Time and Frequency Systems



Courtesy H. Fruehauf, ViaLogy LLC

GPS

GPS Constellation Status



As of 13 March 2021: 32 Satellites, 31 Operational Baseline Constellation: 24 Satellites			
Block	Quantity	Average age (yrs)	Oldest
II-R	8	18.9	23.1
II-RM	7	13.6	15.3
II-F	12	7.0	10.5
III-A	4	2.8	1.2

GPS Signal in Space (SIS) Performance

From 18 Aug 19 to 15 Aug 20

Average URE*	Best Day URE	Worst Day URE
52.2 cm	38.5 cm (1 Jun 20)	90.2 cm (26 Jul 20)

*All User Range Errors (UREs) are Root Mean Square values

GLONASS: GLObal NAvigation Satellite System

GLONASS CONSTELLATION STATUS, 13.03.2021	
Total satellites in constellation	27 SC
Operational	23 SC
In commissioning phase	-
In maintenance	1 SC
Under check by the Satellite Prime Contractor	-
Spares	1 SC
In flight tests phase	2 SC

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

Galileo Status

Summary of satellites, as of 21 January 2021

Block	Launch period	Satellite launches			In operation and healthy
		Full success	Failure	Planned	
GIOVE	2005–2008	2	0	0	0
IOV	2011–2012	4	0	0	3
FOC	From 2014	20	2[α]	12	19
G2G	From 2024	0	0	12	0
Total		26	2	24	22

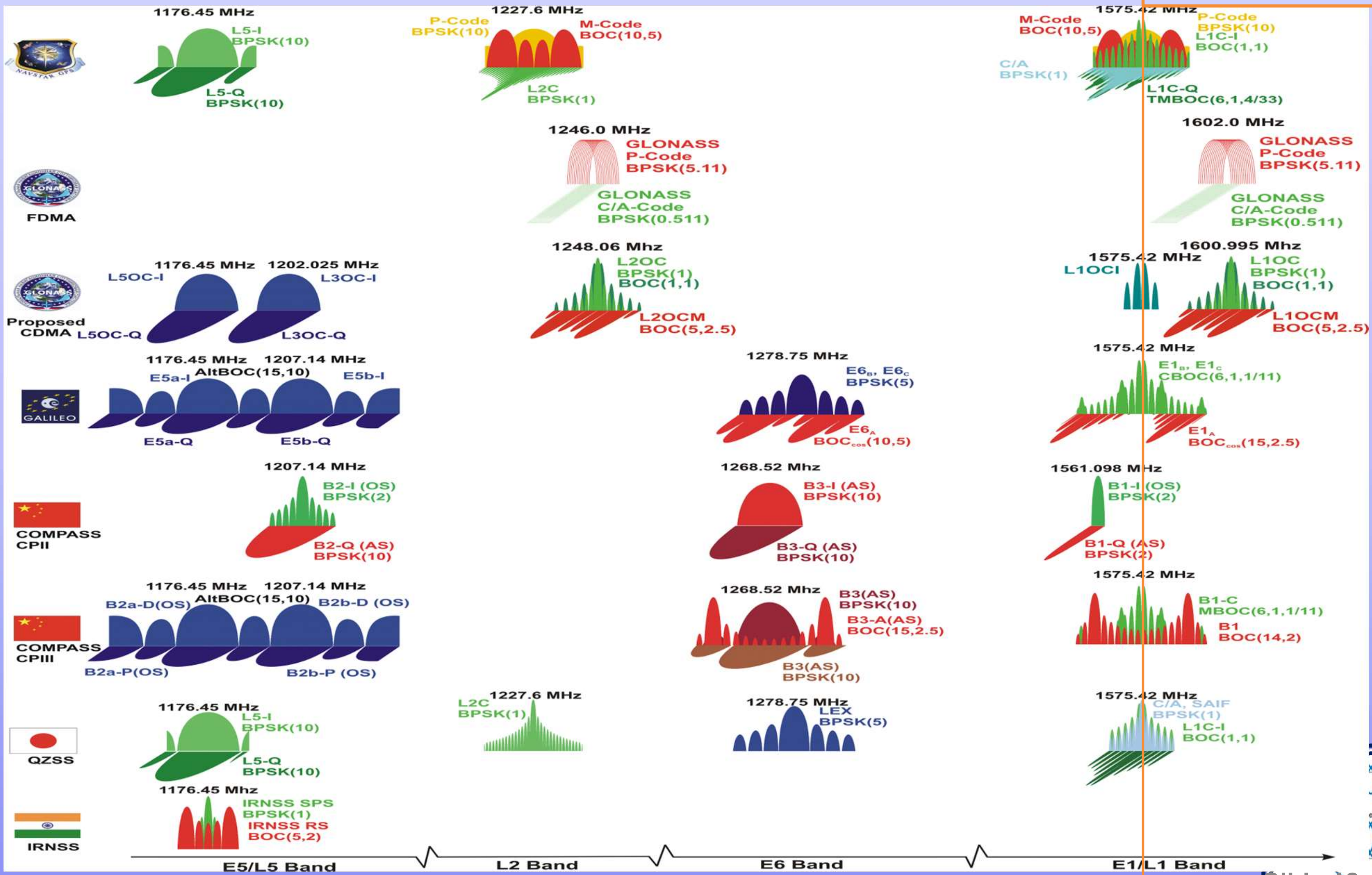
α. Partial failure

BDS-3 Was Formally Commissioned on July 31, 2020

- There are 15 operational BDS-2 satellites (5GEOs + 7IGSOs + 3MEOs, with open service navigation signals B1I/B2I/B3I
- There are 27 operational BDS-3 non-GEO satellites (24 MEOs + 3IGSOs) providing open service for global users with signals B1C/B2a/B1I/B3I/B2b, using PRN from 19 to 61.
- There are 3 BDS-3 GEO satellites providing open service for global users with signals B1I/B3I, BDSBAS-B1C/BDSBAS-B2a and B2b-PPP.

Spectra of GNSS's

Primary Commercial Signal



GNSS Vulnerability

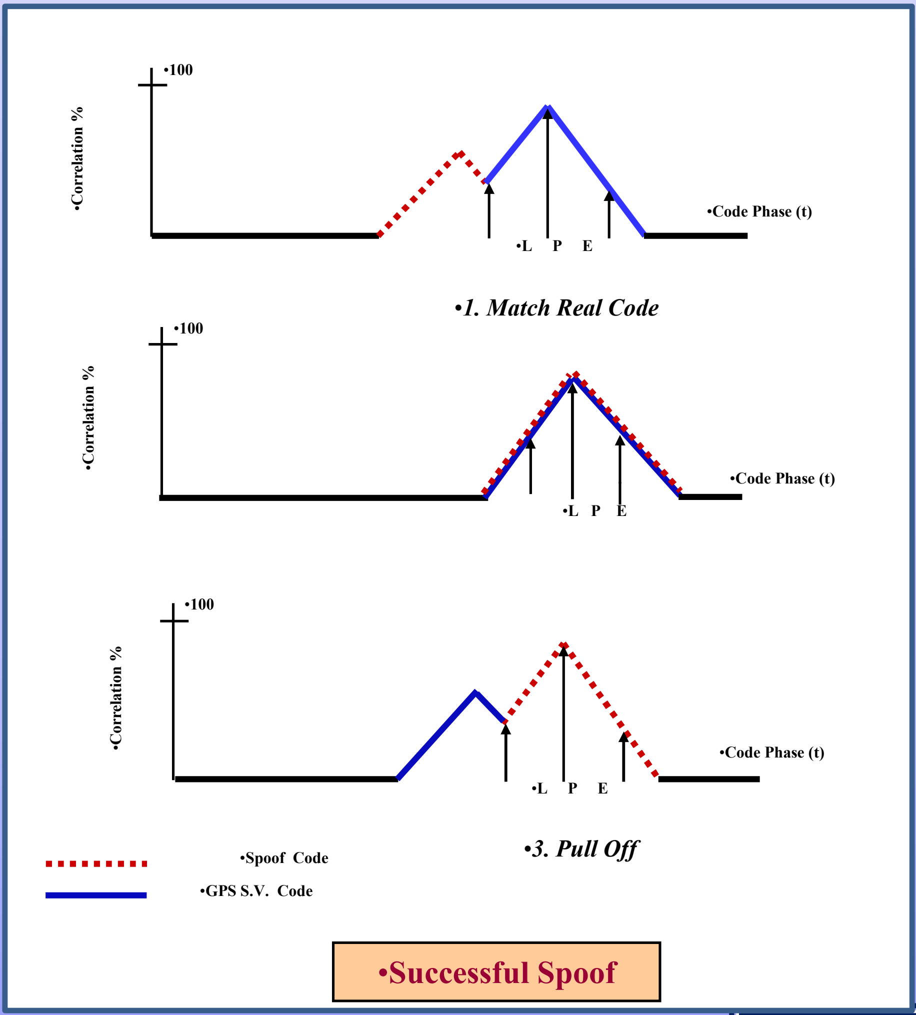
- GNSS best feature and worst problem: it is extremely reliable
- Jamming Power Required at GNSS Antenna
  - On order of a Picowatt (10^{-12} watt)
- Many Jammer Models Exist
  - Watt to MWatt Output – Worldwide Militaries
  - Lower Power (<100 watts); "Hams" Can Make

"Personal Privacy" Device

Military Jammer

Disruption Mechanisms - Spoofing/Meaconing

- Spoof – Counterfeit GNSS Signal
  - C/A Code Short and Well Known
  - Widely Available Signal Generators
- Meaconing – Delay & Rebroadcast
- Possible Effects
  - Long Range Jamming
  - Injection of Misleading PVT Information
- No "Off-the-Shelf" Mitigation



Civil GNSS Spoofing Threat Continuum*

Simplistic | *Intermediate* | *Sophisticated*

Commercial signal simulator | **Portable software radio** | **Coordinated attack by multiple phase-locked spoofers**

*** Courtesy of Coherent Navigation, Inc**

Spoofing example:

'circle spoofing' moves ship locations thousands of miles

New research by Bjorn Bergman of the environmental non-profit SkyTruth has found ships in various parts of the world reporting locations thousands of miles away and circling at precisely 20 knots.

May 26, 2020 – By Dana A. Goward

https://rntfnd.org/2020/05/26/new-gps-circle-spoofing-moves-ship-locations-thousands-of-miles-gps-world/

Conclusions

- GNSSs are very accurate both for time and frequency, many signals free for use, and are very reliable
  - Perhaps their greatest advantage and disadvantage!
  - Signals are subject to interference

Thanks for your attention!

Extra slides follow in the deck.

GPS Modernization

GPS Modernization

SPACE AND MISSILE SYSTEMS CENTER

Space Segment

SV families provide L-Band broadcast to User Segment

GPS IIA/IIR
- Basic GPS
- 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 (SV01-10)
- Accuracy & Power
- Increased Anti-Jam Power
- Inherent Signal Integrity
- 4th Civil Signal (L1C)
- Longer Life
- Better Clocks

GPS IIIF (SV11-32)
- Unified S-Band Telemetry, Tracking & Commanding
- Search & Rescue (SAR) Payload
- Laser Retroreflector Array
- Redesigned NDS Payload

Control Segment

TT&C of Space Segment assets & distribution of data to user interfaces

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

Architecture Evolution Plan (AEP)
- Distributed Architecture
- Increased Signal Monitoring Coverage
- Security
- Accuracy

OCX Block 0
- GPS III Launch & Checkout System

GPS III Contingency Ops (COps)
- GPS III Mission on AEP

M-Code Early Use (MCEU)
- Update OCS to operationalize Core M-Code

OCX Block 1/2
- Fly Constellation & GPS III
- Begin New Signal Control
- Upgraded Information Assurance

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

User Segment

Applies Space and Control Segment data for PNT applications

Continued support to an ever-growing number of applications
- Annual Public Interface Control Working Group (ICWG)
- Standard Positioning Service (SPS) Performance Standard Updates
- Precise Positioning Service (PPS) Enhancements
- Sustained commitment to transparency
- Visit GPS.gov for more info

Modernized Civil Signals
- L2C (Various commercial applications)
- L5 (Safety-of-life, frequency band protected)
- L1C (Multi-GNSS interoperability)

Next Generation GPS Control System

Next Generation Operational Control System (OCX)

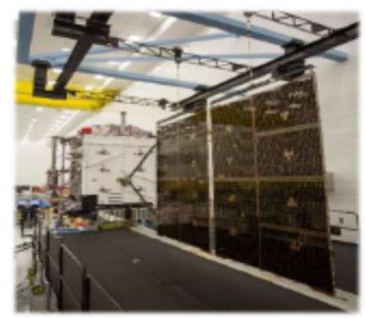
- Next-generation command, control and cyber-defense for GPS
  - Enhanced command and control capability
  - Modernized architecture
  - Robust information assurance and cyber security
- Incremental Development
  - OCX Block 0: Launch and Checkout System (LCS) for GPS III
  - OCX Blocks 1 and 2: Controls and manages all GPS IIR, GPS IIR-M, GPS IIF, and GPS III spacecraft; and controls all legacy and new GPS signals
- Current Status
  - LCS successfully supported GPS III SV01, SV02, and SV03 Launch and Checkout
    - Exceeding operational requirements for availability and dependability
  - OCX Block 1 software coding complete – 12 Aug 19
  - System integration and verification ongoing
  - Ready to Transition to Operations: 4QCY22

OCX program continues to execute and meet schedule

GPS III

GPS III

- SV01 Set healthy and available for use on 13 Jan 20
- SV02 Set healthy and available for use on 1 Apr 20
- SV03 Operationally accepted 27 Jul 20
- SV04 Launch scheduled for 29 Sep 20
  - Second NSSL mission on a recoverable Falcon 9
- SV05 Declared Available for Launch 7 May 20
- SV06 Available for Launch Spring 2021
- SV07 TVAC forecast completion Sep 2020
- SV08 Core Mate completed 15 Apr 20
- SV09-10 Component deliveries in progress



Fourth GPS III satellite launch scheduled 29 Sep

Space Starts Here

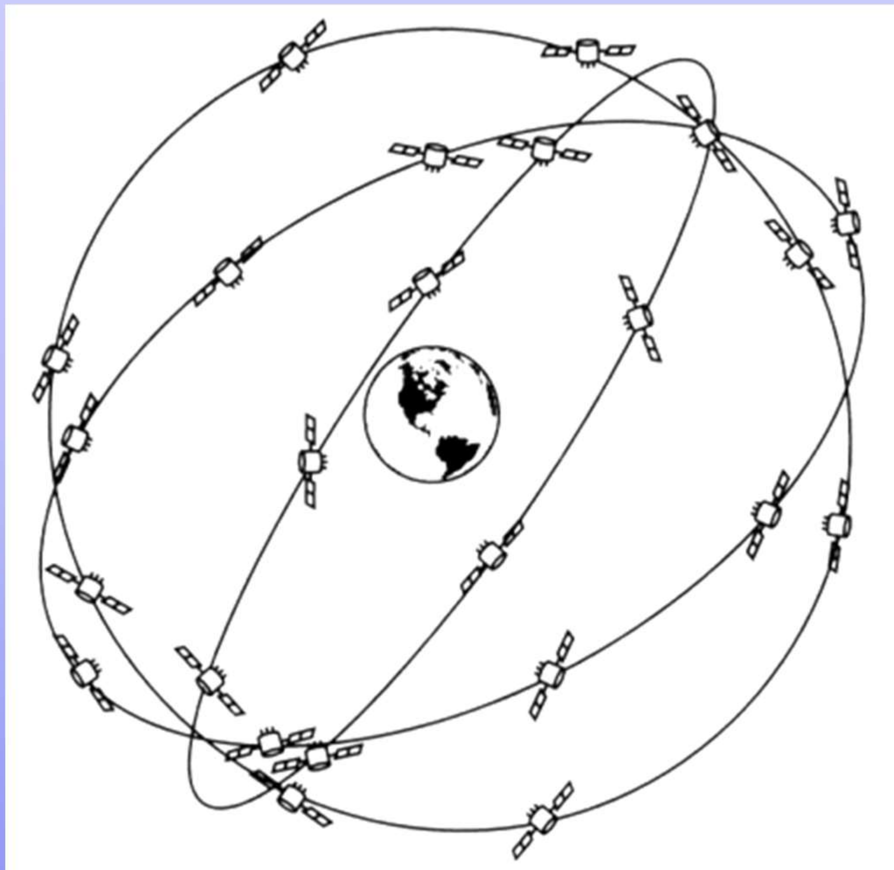
GPS IIIF

GPS III Follow-On (GPS IIIF)

- GPS IIIF additional features
  - Regional Military Protection (RMP) and redesigned Nuclear Detonation Detection System (NDS)
  - Search-and-Rescue (SAR) payload – faster detection and location of distress signals
  - Laser Retroreflector Array (LRA) – provides more precise ranging data
- Partnering with Air Force Research Laboratory (AFRL) for future technology opportunities
  - Digital Reprogrammable Payloads
  - Demo on Navigation Technology Satellite (NTS-3)
  - Near Real-Time Commanding/Crosslinks
- Status: Design Phase Completed 13 Jul 20; SV11 launch forecasted for 2026

Ensuring the Gold Standard today and into the future

GLONASS: GLObal NAvigation Satellite System

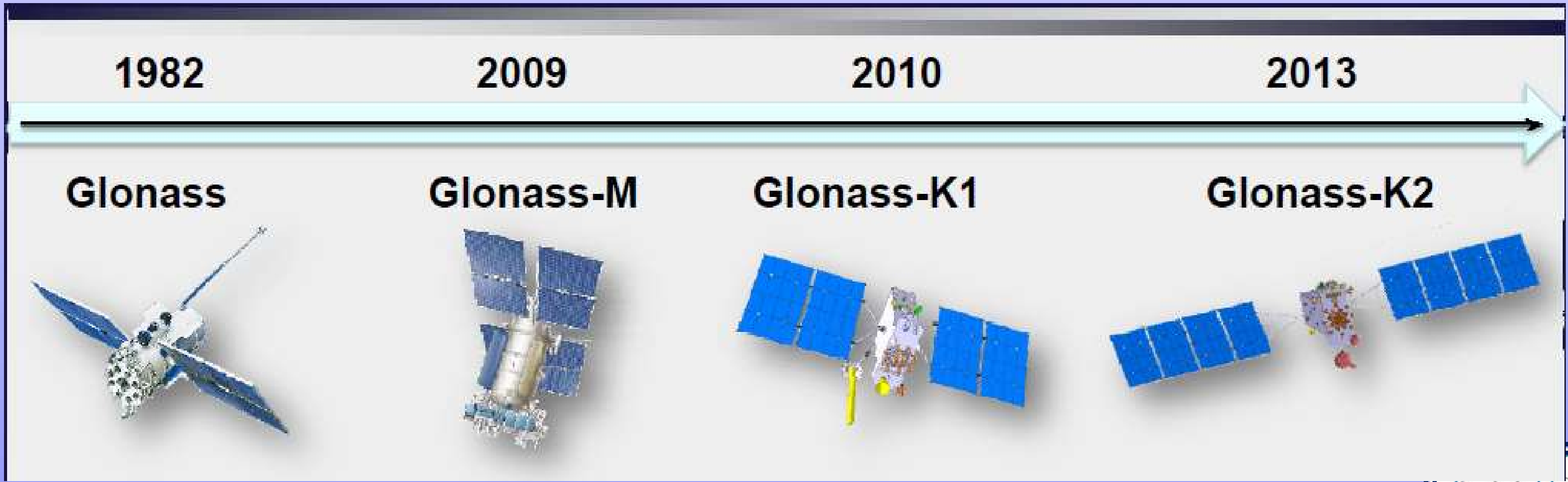


GLONASS Satellite Constellation

- 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

GLONASS Modernization

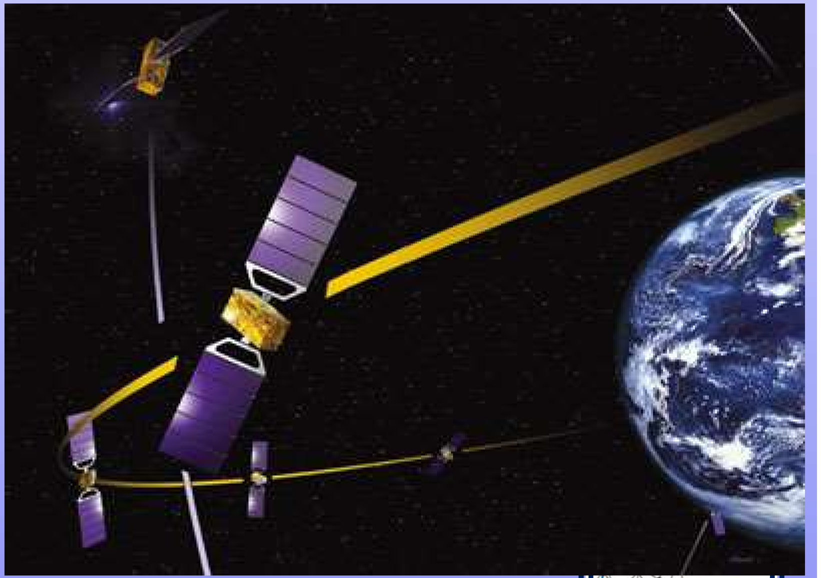
- GLONASS modernization efforts include:
  - Introduction of new CDMA signals for improved interoperability with other GNSS systems
  - Continue to broadcast legacy FDMA signals
  - New GLONASS K satellites with improved accuracy and longer design life
  - Improvements to ground control system



For more information, see:
https://insidegnss.com/third-glonass-k-the-first-in-six-years-to-launch-in-october/

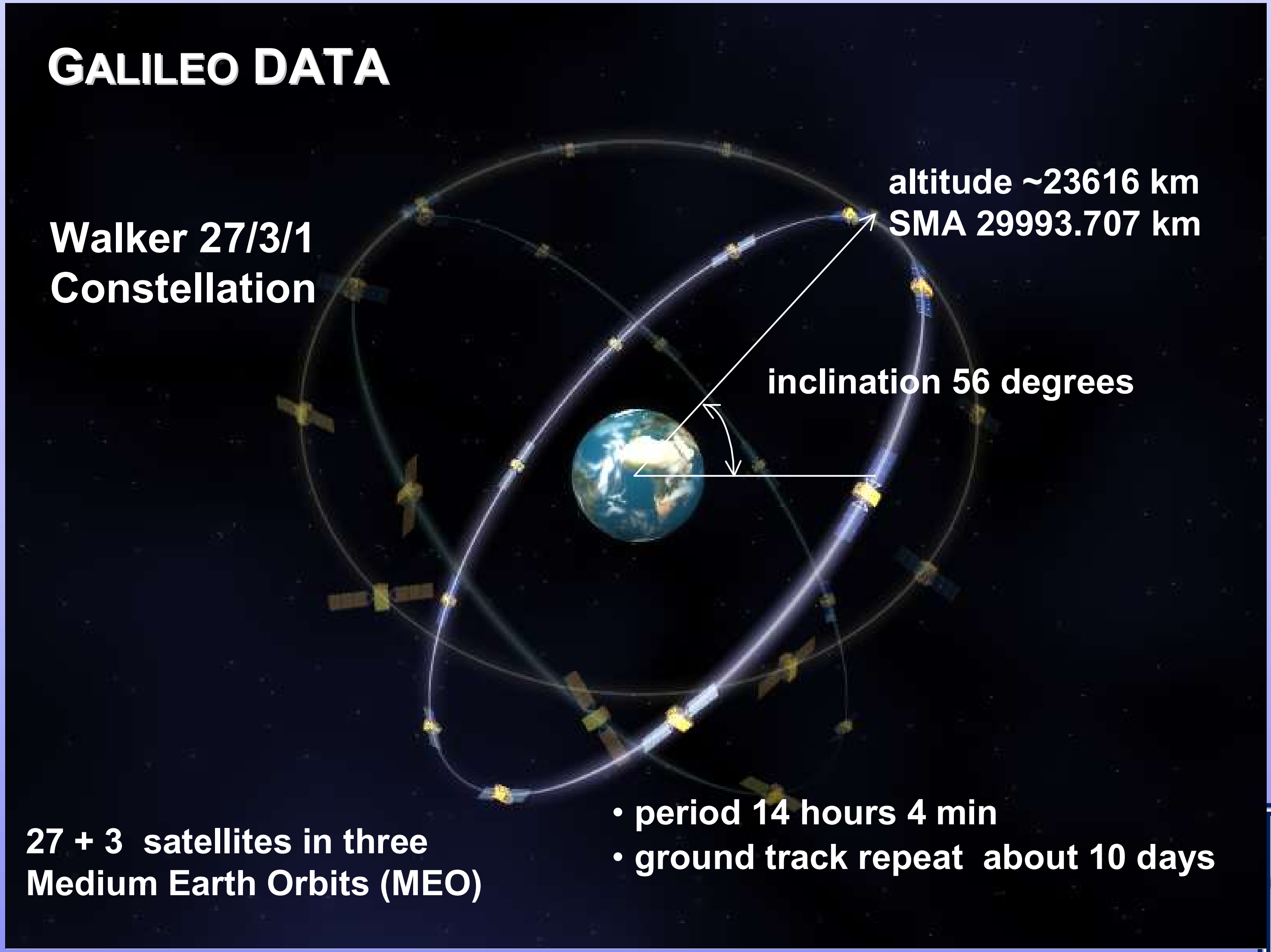
GALILEO

- 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.
- The design 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 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

Galileo Development

- Galileo started offering Early Operational Capability (EOC) on 15 December 2016,
  - providing initial services with a weak signal
  - reached Full Operational Capability (FOC) in 2019.
  - The use of basic (lower-precision) Galileo services is free and open to everyone.
  - The higher-precision capabilities are available for paying commercial users.
  - Galileo is intended to provide horizontal and vertical position measurements within 1-metre
  - better positioning services at higher latitudes than other positioning systems.
  - Also to provide a new global search and rescue (SAR) function as part of the MEOSAR system.
- The complete 30-satellite Galileo system (24 operational and 6 active spares) is expected by the end of 2020.
- It is expected that the next generation of satellites will begin to become operational by 2025
- 2019 outage: 11 to July 2019, the whole constellation signal outage
- The cause was an equipment malfunction affected time and orbit predictions.
- By early 2020, there were 26 live satellites in the constellation
  - 22 in usable condition
  - 2 satellites are in "testing"
  - 2 more not available to users.[
- Out of 22 active satellites:
  - 3 from the IOV (In-Orbit Validation)
  - 19 of the FOC types.
- Galileo system has greater accuracy than GPS
  - Accuracy less than one metre when using broadcast ephemeris (GPS: three metres)[
  - 1.6 centimetre (GPS: 2.3 centimetre) when using real-time corrections for satellite orbits and clocks

Chinese Beidou 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 (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) extended to global coverage in 2020

http://en.beidou.gov.cn/
https://www.gps.gov/cgsic/meetings/2020/geng.pdf

BDS enters a global era

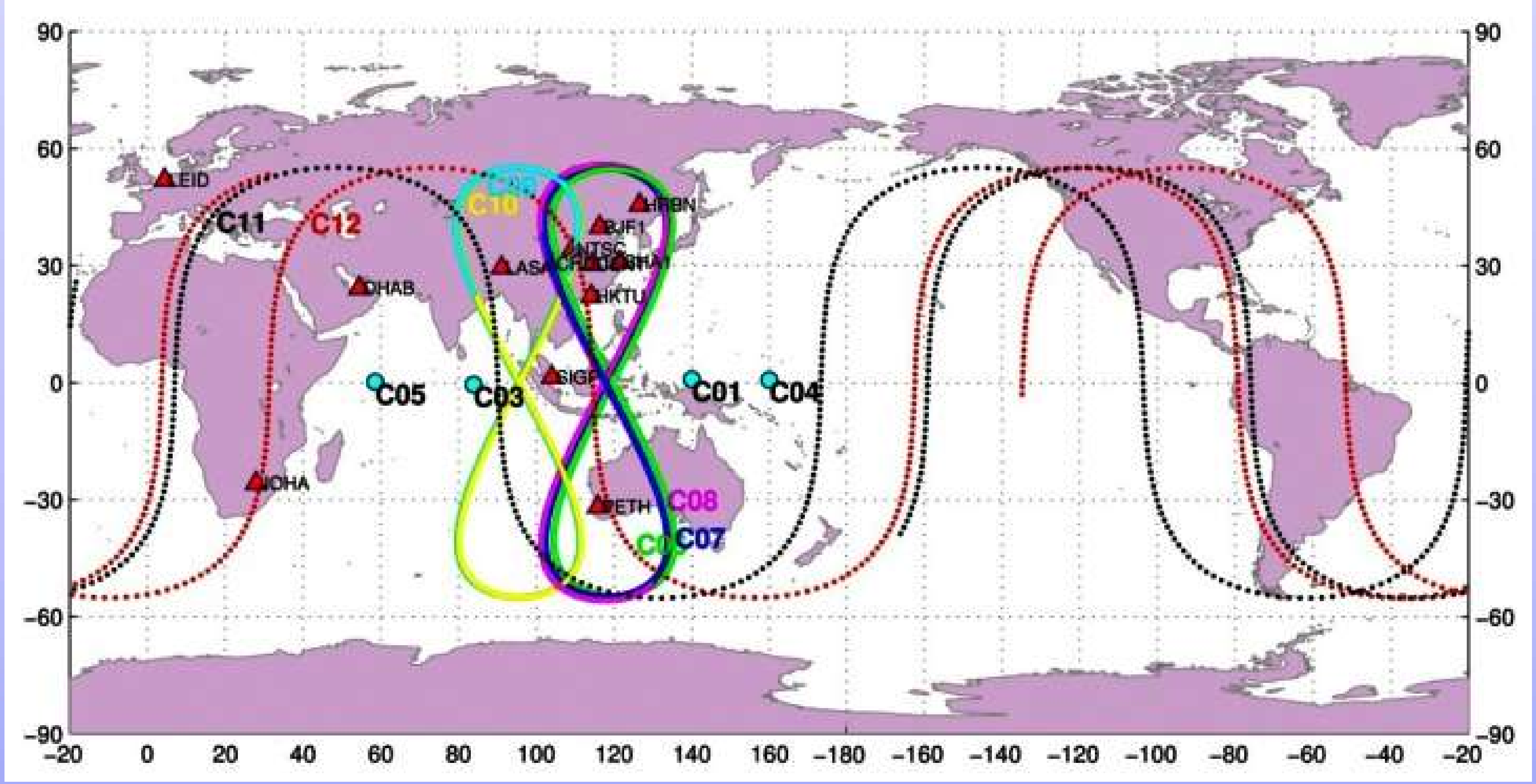
BDS-3 Was Formally Commissioned on July 31, 2020

- The BDS-3 space constellation, consisting of 30 satellites (24MEOs+3GEOs+3IGSOs), were successfully deployed between November 5, 2017 and June 23, 2020.

- Many state of art technologies, such as more reliable atomic clocks, inter-satellite links, and new navigation signals are added.

- In addition to the fundamental PNT services, new services are implemented.

Beidou Ground Tracks
for Three Types of Orbits



Ground tracks of BDS GEO satellites (C01, C03, C04, C05), IGSO satellites (C06, C07, C08, C09, G10), and MEOs (C11, C12) and station distribution of the BETS experimental tracking stations.

From "Estimating Zenith Tropospheric Delays from BeiDou Navigation Satellite System Observations", *Sensors* 2013, *13*, 4514-4526; doi:10.3390/s130404514

SDR is making Spoofing Easy

Standard Engineering School classes teach techniques for signal generation that easily apply to spoofing

GNSS References

- GPS
  - CGSIC 2020 https://www.gps.gov/cgsic/meetings/2020/
  - Coast Guard Nav Center http://www.navcen.uscg.gov/
- Galileo http://www.gsc-europa.eu/system-status/Constellation-Information
- Glonass http://www.sdcm.ru/smglo/grupglo?version=eng&site=extern
- Beidou:
  - IGS page http://igs.org/mgex/Status_BDS.htm

- General
  - GPS World http://gpsworld.com/
  - Inside GNSS http://www.insidegnss.com/