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Frequency and Time from Radio: Time & Frequency Transfer and GNSS

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Time & Frequency Transfer and GNSS

- Intro: Time and Frequency Signals
- GNSS
- GNSS Failure Modes and Vulnerabilitites
- Conclusions & References

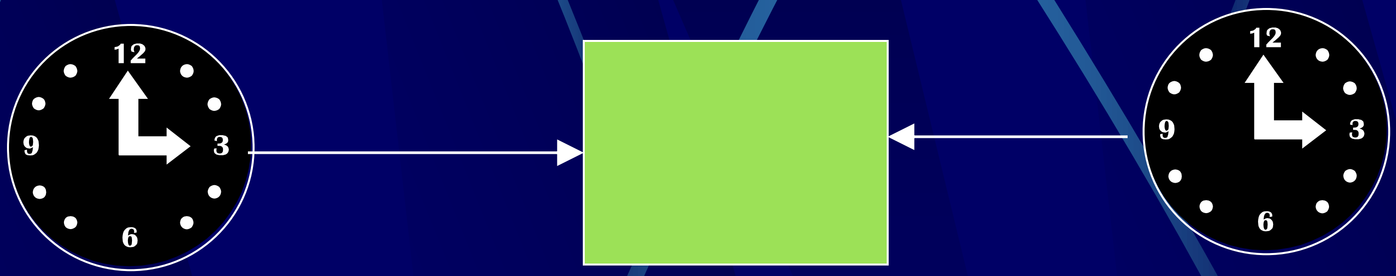
Time and Frequency Transfer

- It’s all about the transfer Delay and Convenience
- Accuracy and Stability are the Concerns
  - Time Transfer Accuracy Requires Calibrating Delays
  - Time Stability = Frequency Accuracy
- Delivery Styles
  - Continuous vs. Intermittent
  - Comparison vs. Lock local clock

Dissemination or Comparison System

Clock 1

Clock 2



Clock 1
Systematics
and Noise

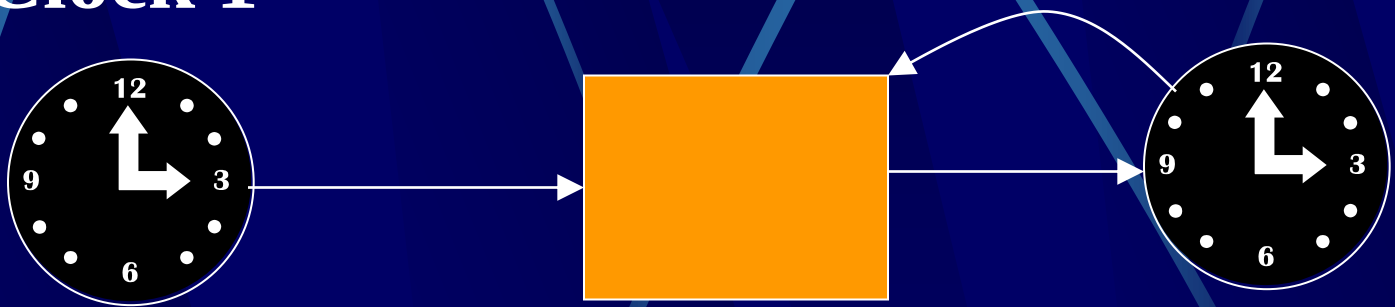
Delay, Perturbations, and
Measurement Noise

Clock 2
Systematics
and Noise

Clock Hierarchies

Clock 1

Clock 2

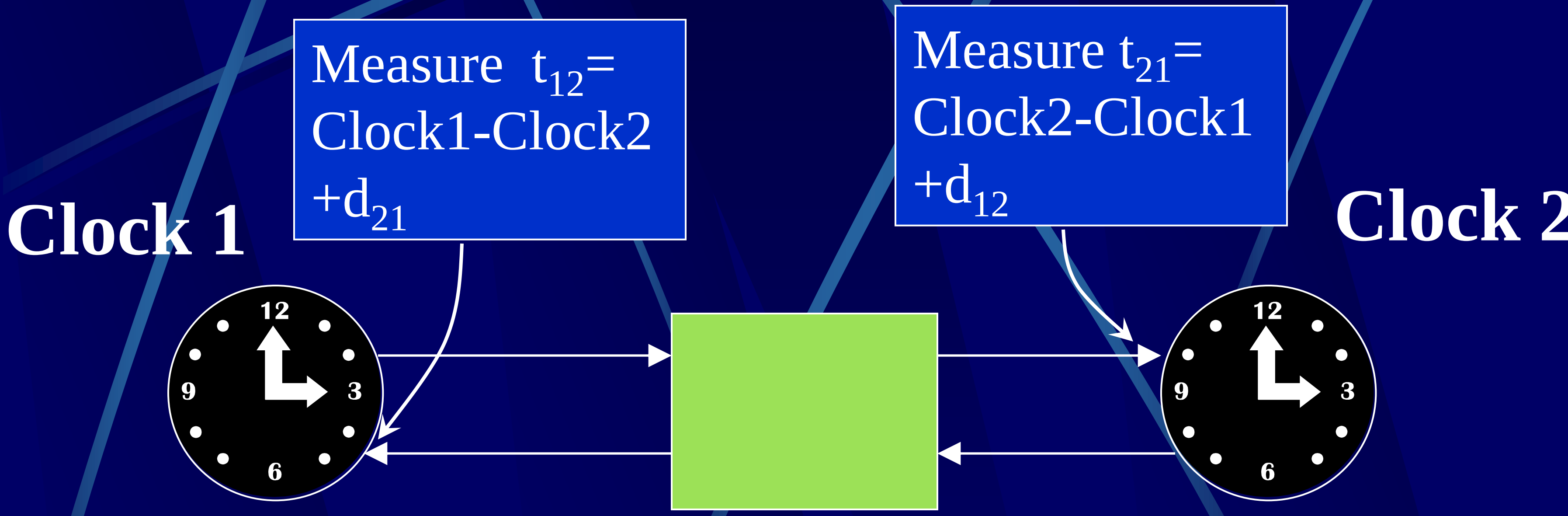


Clock 1 Systematics and Noise

Lock Loop Systematics and Noise: Contributions from Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Two -Way Comparison System



Clock 1 Systematics and Noise

Measurement Noise and Path Perturbations Largely Reciprocal:

$d_{21} = d_{12}$

Clock 2 Systematics and Noise

Ideal Two-Way Computation

- Measure t_{21}= Clock2 - Clock1 +d_{12}
- Measure t_{12}= Clock1 – Clock2 +d_{21}
- Reciprocity: $d_{12=}$ d_{21}

- Therefore
  - Delay= ½ (t_{12} + t_{21})
  - Clock1 – Clock2 = ½ (t_{12} - t_{21})

Time and Frequency Transfer: Desired Quantities

- Time Transfer Accuracy Requires Calibrating Delays

- Time Stability = Frequency Accuracy

Time & Frequency Transfer and GNSS

- Intro: Time and Frequency Signals
- GNSS
  - GPS
  - GLONASS
  - Galileo
  - Beidou/Compass
- GNSS Failure Modes and Vulnerabilitites
- Conclusions & References

Two Messages About GNSS

1. GNSS are robust and growing and provide real-time UTC time and navigation in a ++$10B industry

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

The Family of Global Navigation Systems

GPS	Galileo	GLONASS	Beidou/Compass
US	EU	Russia	China
(24+, Now 32)	(27, Now 4 IOV)	(24, Now 24)	(35, Now 14)

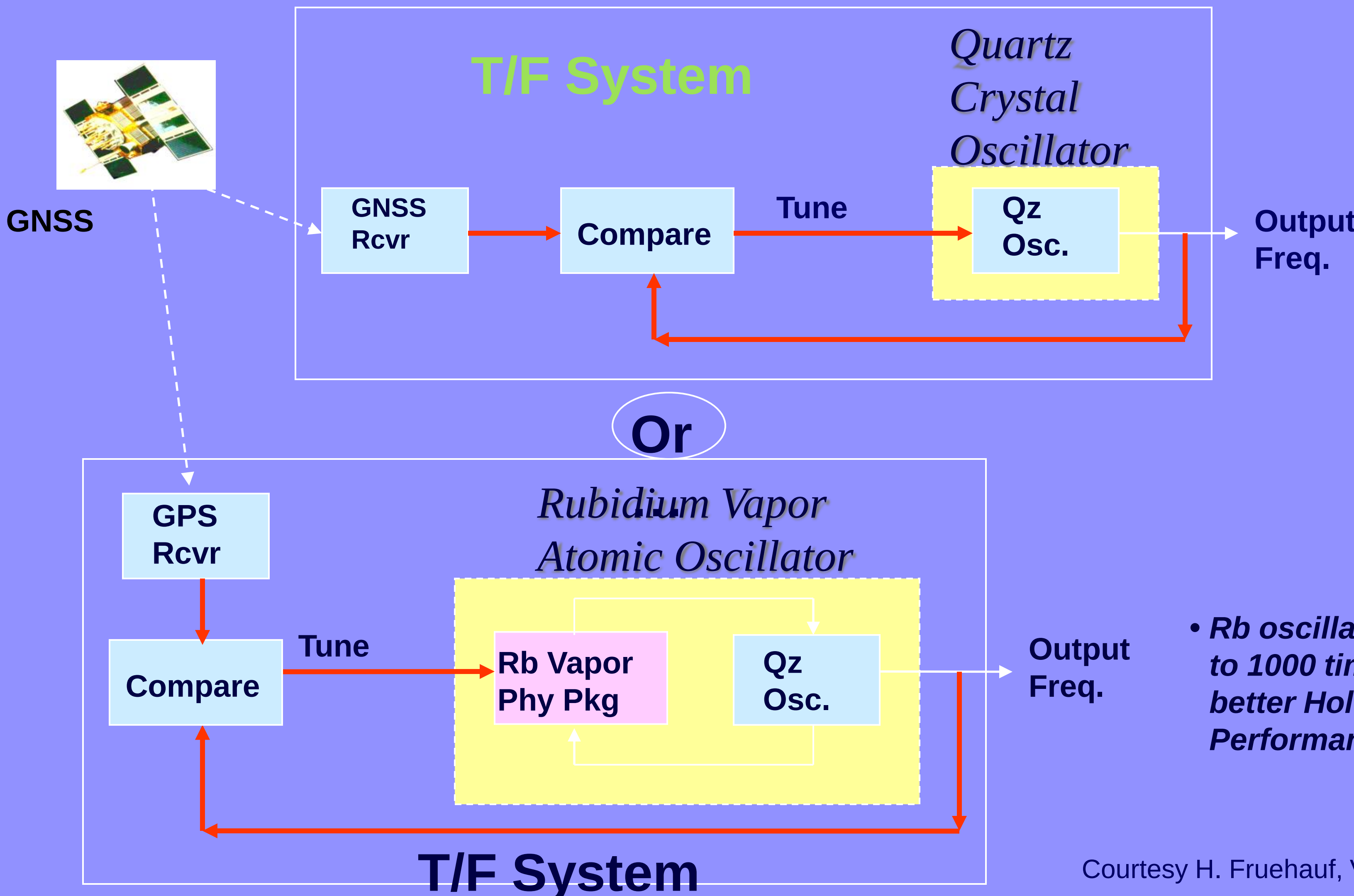
GNSS Systems: General Properties

- 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

GNSS Systems: General Properties

- All signals are weak
  - E.g. GPS is ~-160dBm
  - All are deliberately well below the noise until the process gain
- Signals are clustered in the spectrum
- Hence it is relatively easy to jam GNSS and becoming easy to spoof

GNSS-aided Time and Frequency Systems



- ***Rb oscillator 100 to 1000 times better Holdover Performance***

Courtesy H. Fruehauf, ViaLogy LLC

GPS

GPS Modernization – New Civil Signals

- **Second civil signal "L2C"**
  - Designed to meet commercial needs
  - Available since 2005 without data message
  - Phased roll-out of CNAV message
  - Currently 9 SVs in operation

- **Third civil signal "L5"**
  - Designed to meet transportation safety-of-life requirements
  - Uses Aeronautical Radio Navigation Service band
  - Currently 2 SVs in operation

- **Fourth civil signal "L1C"**
  - Designed for GNSS interoperability
  - Specification developed in cooperation with industry
  - Launches with GPS III in 2015
  - Improved tracking performance

Urban Canyons

Improved performance in challenged environments

Early CNAV test capability currently in development

GPS IIF Status

- **Launched GPS IIF-2 on 16 Jul 11**
  - Satellite Vehicle Number 63, PRN 1
  - Set healthy 14 Oct 11
  - Second operational L5 signal
  - Providing enhanced GPS clock performance
- **2 total GPS IIFs on orbit**
  - Best accuracies in constellation (0.38 m RMS)
  - Demonstrated Flex Power capability
- **10 more GPS IIFs in the pipeline**
  - SVs 5-7 are in storage
  - SVs 3, 8 and 9 in assembly, integration and test
  - On-track to complete all production by Summer 2013
- **Next GPS IIF Launch scheduled for 4 Oct 12**

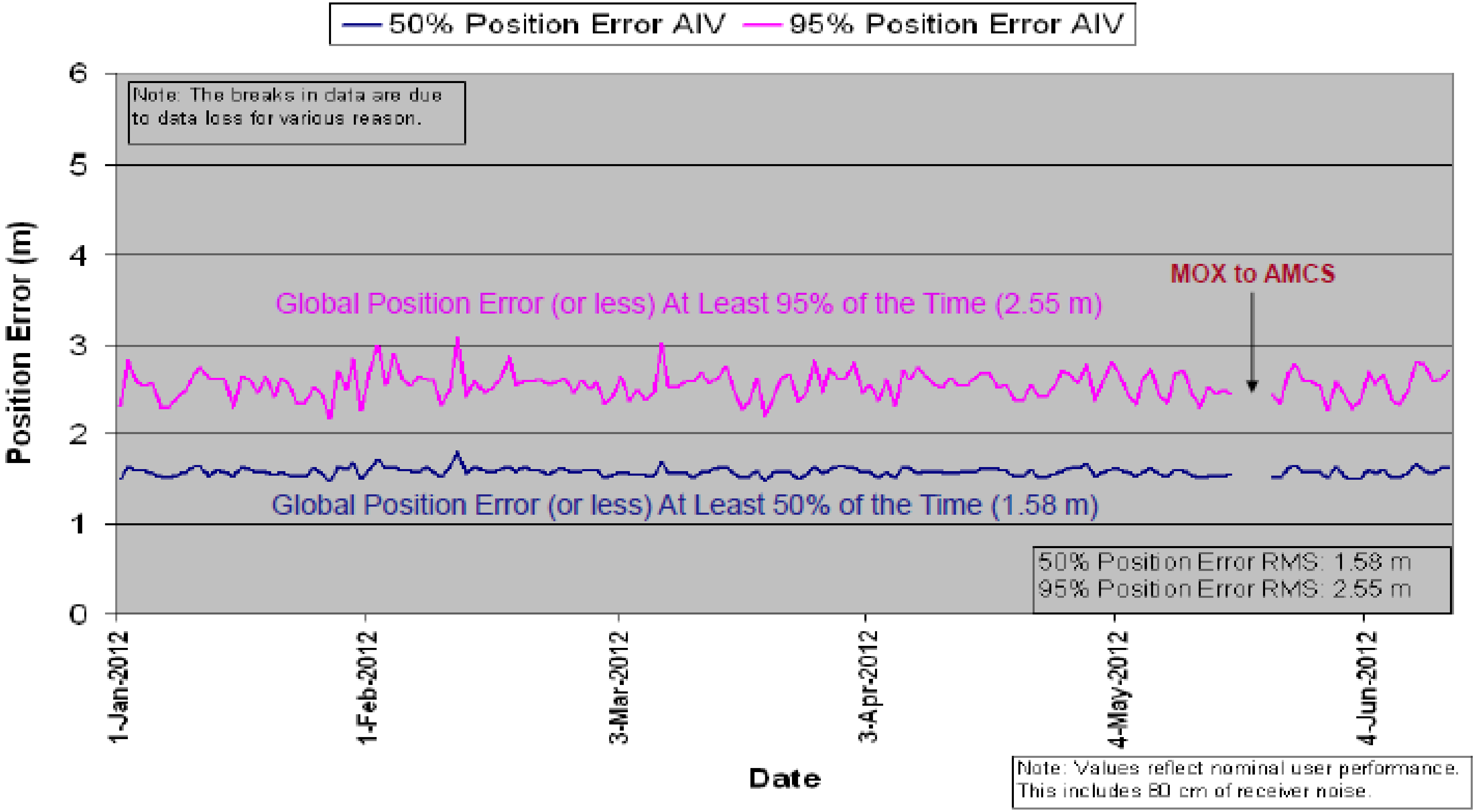
This launch was successful!

U.S. AIR FORCE

Accuracy – All in View Solution

GLOBAL GPS PERFORMANCE (1 Jan – 14 Jun 2012)

Nominal User Performance



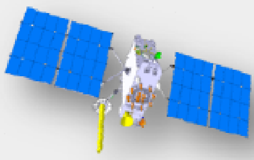
GPS III Status

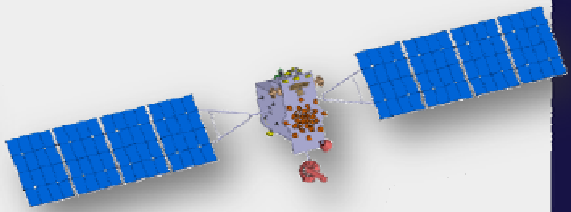
- **Newest block of GPS satellites**
  - First satellite to broadcast common L1C signal
  - Multiple civil and military signals; L1 C/A, L1 P(Y), L1M, L1C, L2C, L2 P(Y), L2M, L5
  - Three Rubidium clocks
- **SV01 initial power turn-on 1QFY13**
- **GPS Processing Facility (GPF) ribbon cutting**
- **GPS Satellite Simulation delivered**
- **Factory to Factory link established June 2012**

GLONASS

GLONASS Modernization Plan

1982	2003	2011	2013-2014
"Glonass"	"Glonass-M"	"Glonass-K1"	"Glonass-K2"





"Glonass" (1982)

- 3 year design life
- Clock stability - $5*10^{-13}$
- Signals: L1SF, L2SF, L1OF, (FDMA)
- Totally launched 81 satellites
- Real operational life time 4.5 years

"Glonass-M" (2003)

- 7 year design life
- Clock stability $1*10^{-13}$
- Signals: Glonass + L2OF (FDMA)
- Totally launched 28 satellites and going to launch 8 satellite by the end 2012

"Glonass-K1" (2011)

- 10 year design life
- Unpressurized
- Expected clock stability ~10…$5*10^{-14}$
- Signals: Glonass-M + L3OC (CDMA) – test
- SAR

"Glonass-K2" (2013-2014)

- 10 year design life
- Unpressurized
- Expected clock stability ~5…$1*10^{-14}$
- Signals: Glonass-M + L1OC, L3OC, L1SC, L2SC (CDMA)
- SAR

CDMA signals general structure already designed

Presented by
Ekaterina Oleynik, Sergey Revnivykh, Central Research Institute of Machine Building
Civil GPS Service Interface Committee, Portland, Oregon, 19th September 2011

Glonass Constellation Status, 23 Oct 2012

Total satellites in constellation	31 SC
Operational	24 SC
In commissioning phase	-
In maintenance	3 SC
Spares	3 SC
In flight tests phase	1 SC

Galileo

Galileo Implementation Plan

2014

•**INITIAL OPERATIONAL CAPABILITY** (IOC) 18 satellites in orbit for under 4m horizontal accuracy

•interoperable with GPS for increased accuracy (current receivers would be simply required to get firmware updates)

2020

•**FULL OPERATIONAL CAPABILITY** Complete constellation operational (27+3 satellites)

•Stand-alone GALILEO can be used to critical applications

Galileo Successful Launch October 12

- The two new Galileo satellites will join the first two spacecraft orbited on October 21, 2011
- Once all four are operational in space, they will provide the minimum number of satellites required for navigational fixes — enabling system validation testing when all are visible in the sky.

GALILEO System Architecture

- A constellation of 30 satellites in Medium-Earth Orbit (MEO). Each satellite will contain a navigation payload and a search and rescue transponder;
- 30-40 sensor stations;
- 3 control centres;
- 9 Mission Uplink stations;
- 5 telemetry, tracking and command (TT&C) stations.

Galileo Services

- **Open Service**: basic signal provided free-of-charge;
- **Safety-of-Life Service**: Enhanced signal including an integrity function that will warn the user within a few seconds in case of a malfunction. This service will be offered to the safety-critical transport community e.g. aviation. It will be certified according to the applicable standards e.g. those of the International Civil Aviation Organisation (ICAO) and to the Open Sky regulations;
- **Commercial Service:** combination of two encrypted signals for higher data throughput rate and higher accuracy authenticated data;
- **Public Regulated Service**: two encrypted signals with controlled access for specific users like governmental bodies;
- **Search And Rescue Service**: Galileo will contribute to the international COSPAS-SARSAT cooperative system for humanitarian search and rescue activities. Each satellite will be equipped with a transponder transferring the distress signal from the user to the Rescue Coordination Centre and informing him that his situation has been detected.

Beidou/Compass

COMPASS Roadmap

- Phase 1 (2003+) consists of an experimental regional navigation system, BeiDou-1, which provided active navigation service.
- Phase 2 (2012+) BeiDou-2 consists of a reduced satellite constellation and provides open service over China. This phase aims at deploying a system with passive positioning and timing capability over a regional area.
- Phase 3 (2020+) By 2020, COMPASS would reach full operational capability with a Walker constellation of 27 MEOs plus 5 GEOs and the existing 3 IGSOs satellites of the regional system.

COMPASS Status

- By December 2011 operation on a trial basis
  - Initial passive positioning navigation and timing services for the whole Asia-Pacific region
  - Constellation of 10 satellites (5 GEO satellites and 5 IGSO satellites) and the Initial Operational Service was declared officially available.
- During 2012
  - Three launches where made in February, April and September
  - Added one additional GEO and four MEO satellites
  - In-line with the objective of expanding the service area to Asian-Pacific users and improving service performance (positioning accuracy better than 10 meters).
  - Currently 5 GEO + 5 IGSO + 4 MEO which corresponds to 14 operational satellites of the 35 planned.

COMPASS General Services

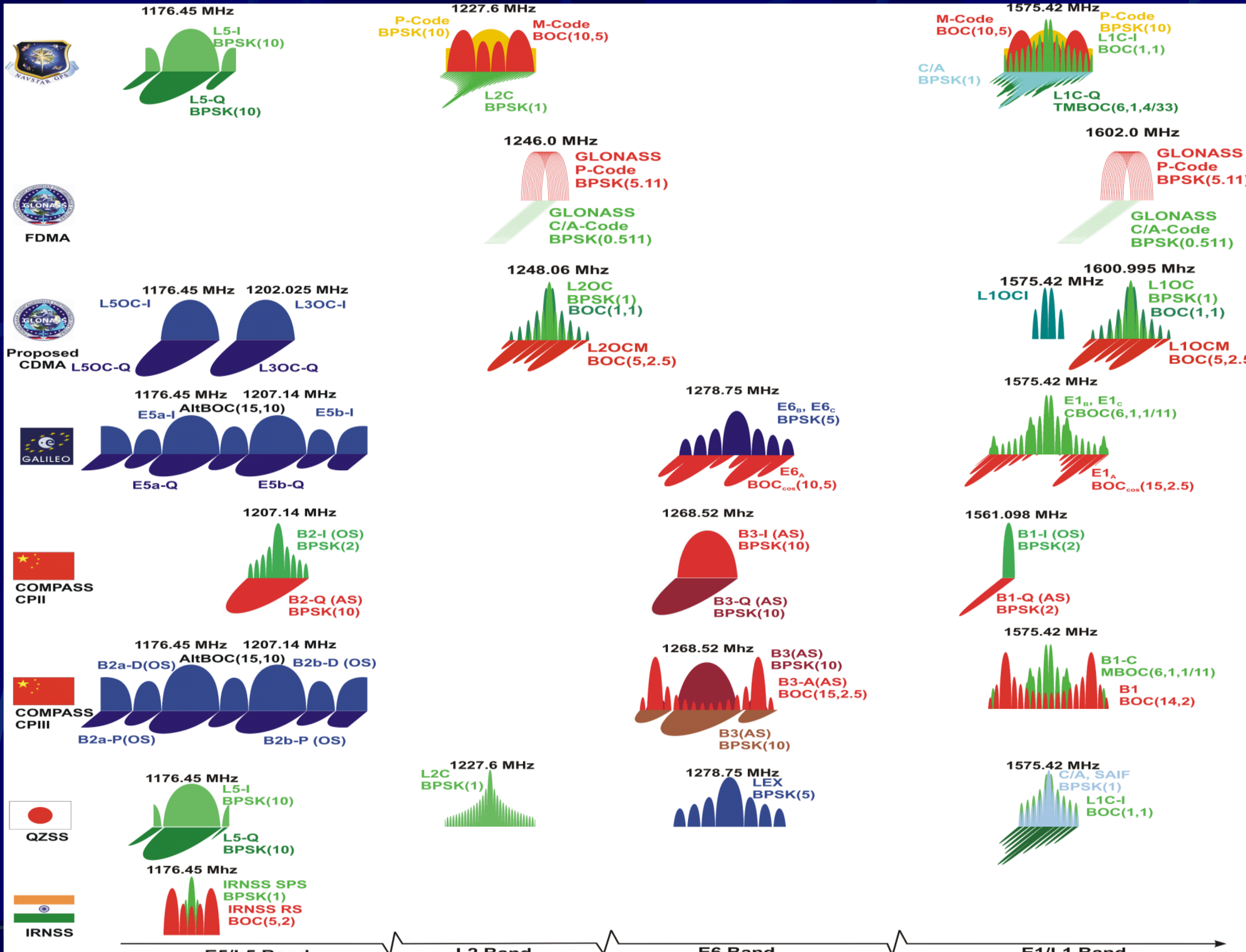
- Radio Determination Satellite Service (RDSS):
  - the user position is computed by a ground station using the round trip time of signals exchanged via GEO satellite.
  - Short message communication (guaranteeing backward compatibility with BeiDou-1)
  - Large volume message communication
  - Information connection
  - Extended coverage
- Radio Navigation Satellite Service (RNSS): very similar to GPS and Galileo

BeiDou-1 Satellites

Date	Satellite	Usable
10/31/2000	BeiDou-1A	?
12/21/2000	BeiDou-1B	Yes
5/25/2003	BeiDou-1C	Yes
2/3/2007	BeiDou-1D	No

BeiDou-2 (Compass) Satellites as of 18 Sep 2012

Date	Satellite	Usable
4/14/2007	Compass-M1	Testing only
4/15/2009	Compass-G2	No
1/17/2010	Compass-G1	Yes
6/2/2010	Compass-G3[47]	Yes
8/1/2010	Compass-IGSO1	Yes
11/1/2010	Compass-G4	Yes
12/18/2010	Compass-IGSO2[49]	Yes
04/10/2011	Compass-IGSO3[50]	Yes
07/26/2011	Compass-IGSO4[51]	Yes
12/02/2011	Compass-IGSO5	Yes
02/24/2012	Compass-G5	Yes
04/29/2012	Compass-M3	Yes
04/29/2012	Compass-M4	Yes
09/18/2012	Compass-M5	Yes
09/18/2012	Compass-M6	Yes



1176.45 MHz
L5-I
BPSK(10)
L5-Q
BPSK(10)
1227.6 MHz
P-Code
BPSK(10)
M-Code
BOC(10,5)
L2C
BPSK(1)
1575.42 MHz
M-Code
BOC(10,5)
P-Code
BPSK(10)
L1C-I
BOC(1,1)
C/A
BPSK(1)
L1C-Q
TMBOC(6,1,4/33)
1246.0 MHz
GLONASS
P-Code
BPSK(5.11)
GLONASS
C/A-Code
BPSK(0.511)
1602.0 MHz
GLONASS
P-Code
BPSK(5.11)
GLONASS
C/A-Code
BPSK(0.511)
FDMA
1248.06 Mhz
L2OC
BPSK(1)
BOC(1,1)
L2OCM
BOC(5,2.5)
1600.995 Mhz
1575.42 MHz
L1OCI
L1OC
BPSK(1)
BOC(1,1)
L1OCM
BOC(5,2.5)
1176.45 MHz
1202.025 MHz
L5OC-I
L3OC-I
Proposed
CDMA
L5OC-Q
L3OC-Q
1176.45 MHz
1207.14 MHz
E5a-I
AltBOC(15,10)
E5b-I
GALILEO
E5a-Q
E5b-Q
1278.75 MHz
$E6_B$, $E6_C$
BPSK(5)
$E6_A$
$BOC_{cos}(10,5)$
1575.42 MHz
$E1_B$, $E1_C$
CBOC(6,1,1/11)
$E1_A$
$BOC_{cos}(15,2.5)$
1207.14 MHz
B2-I (OS)
BPSK(2)
B2-Q (AS)
BPSK(10)
COMPASS
CPII
1268.52 Mhz
B3-I (AS)
BPSK(10)
B3-Q (AS)
BPSK(10)
1561.098 MHz
B1-I (OS)
BPSK(2)
B1-Q (AS)
BPSK(2)
1176.45 MHz
1207.14 MHz
AltBOC(15,10)
B2a-D(OS)
B2b-D (OS)
COMPASS
CPIII
B2a-P(OS)
B2b-P (OS)
1268.52 Mhz
B3(AS)
BPSK(10)
B3-A(AS)
BOC(15,2.5)
B3(AS)
BPSK(10)
1575.42 MHz
B1-C
MBOC(6,1,1/11)
B1
BOC(14,2)
1176.45 MHz
L5-I
BPSK(10)
L5-Q
BPSK(10)
QZSS
1227.6 MHz
L2C
BPSK(1)
1278.75 MHz
LEX
BPSK(5)
1575.42 MHz
C/A, SAIF
BPSK(1)
L1C-I
BOC(1,1)
1176.45 Mhz
IRNSS SPS
BPSK(1)
IRNSS RS
BOC(5,2)
IRNSS
E5/L5 Band
L2 Band
E6 Band
E1/L1 Band

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Factors Impacting GPS Vulnerability

- Very Low Signal Power
- Single Civil Frequency
  - Known Signal Structure
- Spectrum Competition
- Worldwide Military Applications Drive a GPS Disruption Industry
  - Jamming Techniques are Well Known
  - Devices Available, or Can be Built Easily
  - Desire for "Personal Privacy" devices

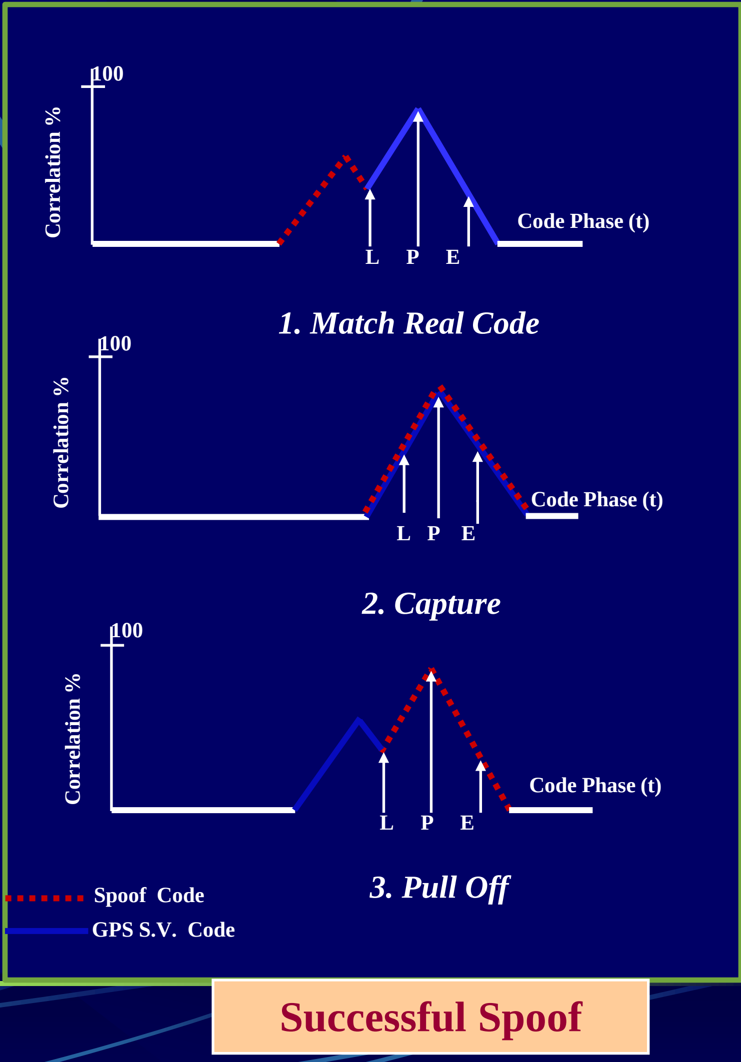
Disruption Mechanisms – Jamming

- Jamming Power Required at GPS 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
- Jamming Signal Types
  - Narrowband
  - Broadband
  - Spread Spectrum - PRN Modulation

Russian Jammer

Disruption Mechanisms - Spoofing/Meaconing

- Spoof – Counterfeit GPS 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



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Conclusions

- GNSS Now
  - Global GPS civil service performance commitment met/exceeded continuously since Dec 93
  - Glonass operational, committed to replenish
  - Galileo, Compass with new satellites
  - Augmentation systems exist
- GNSS Future
  - GPS: new signals, more accuracy, yet backward compatible, more integrity information
  - New/other systems: Glonass, Galileo, Compass, QZSS
  - New services: LBS, Integrity assurance
- GPS/GNSS vulnerabilities
  - GNSS must not be over-relied upon
  - Receiver systems should detect anomalies
- Many resources are available

GPS & U.S. Resources

- GPS.gov
- U.S. Coast Guard Navigation Information Center
  - Voice Announcement ++1-703-313-5907
  - Resource Person ++1-703-313-5900
  - Web Page http://www.navcen.uscg.gov/
  - Civil GPS Service Interface Committee (CGSIC) – GNSS status and other info: http://www.navcen.uscg.gov/cgsic/meetings/48thMeeting/48th_CGSIC_agenda_final.htm
- U.S. Space-Based Positioning, Navigation, and Timing Policy: http://pnt.gov/policy/
- US Timing Labs
  - NIST info: http://www.boulder.nist.gov/timefreq/index.html
  - U.S. Naval Observatory: http://tycho.usno.navy.mil/gpstt.html

GNSS Resources

- General
  - GPS World: www.gpsworld.com
  - Inside GNSS: www.insidegnss.com
  - Institute of Navigation www.ion.org
  - International GNSS Service (IGS) http://igscb.jpl.nasa.gov/
  - ESA Navipedia http://www.navipedia.net/index.php/Main_Page
- GLONASS
  - http://www.spacecorp.ru/en/press/publications/item2738.php
  - http://www.navipedia.net/index.php/GLONASS_Future_and_Evolutions
- Galileo
  - http://ec.europa.eu/enterprise/policies/satnav/galileo/why/index_en.htm
  - http://www.esa.int/esaNA/galileo.html
- Compass
  - http://www.dragoninspace.com/navigation/compass-beidou2.aspx
  - www.beidou.gov.cn