GNSS Signal Structures

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23 January 2018

Introduction

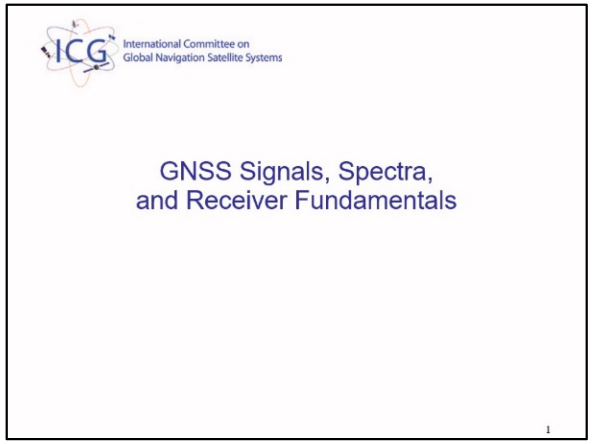
It's a pleasure to speak with you this morning. What follows are excerpts from three separate presentations.

Regards,

Tom Stansell

Stansell Consulting

Source Presentations



GNSS Modernization and Interoperability

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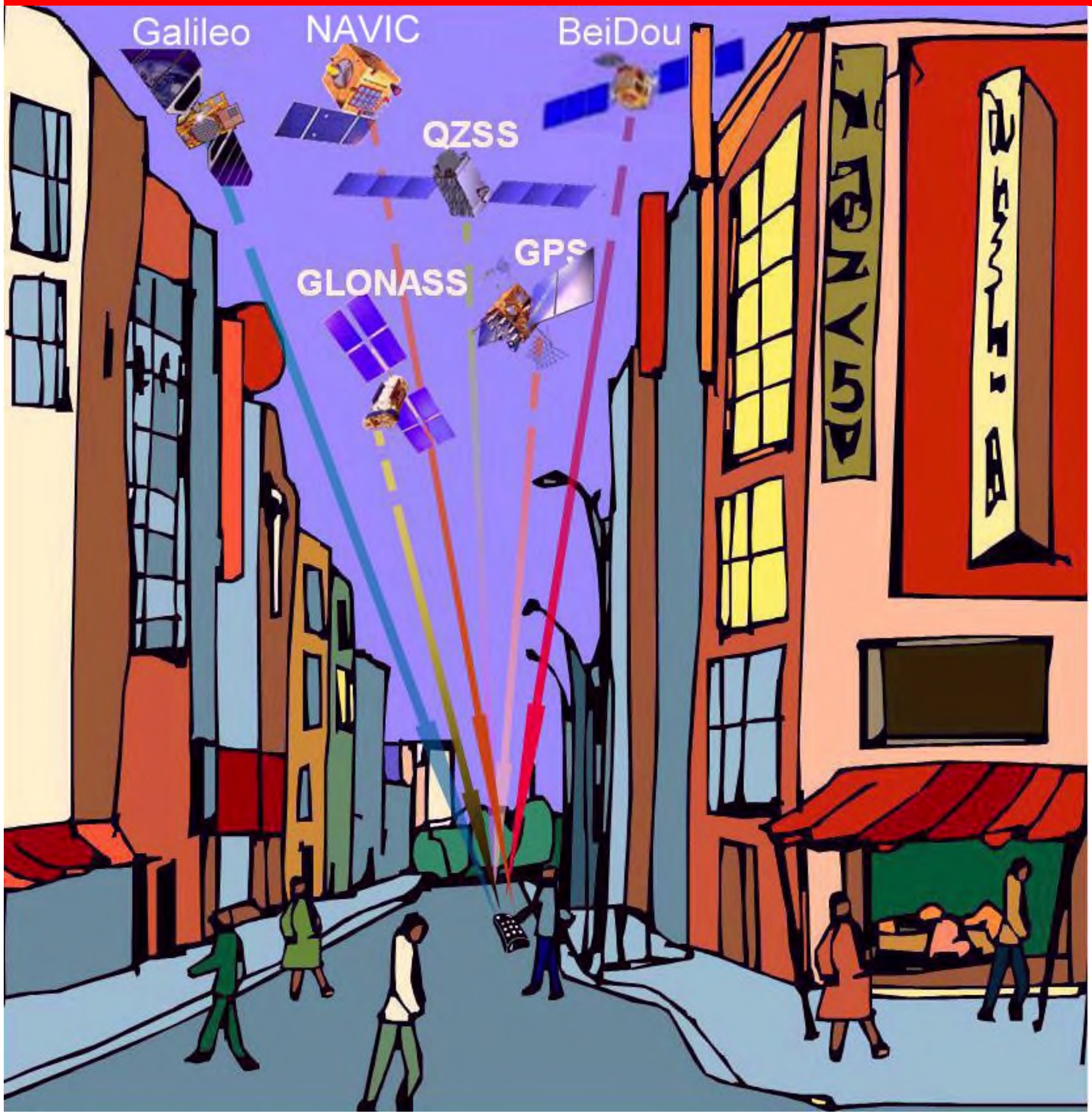
The Goal of Interoperability



- Ideal interoperability allows navigation with **one signal each** from four or more systems **with no additional receiver cost or complexity**

Interoperable = Better Together than Separate

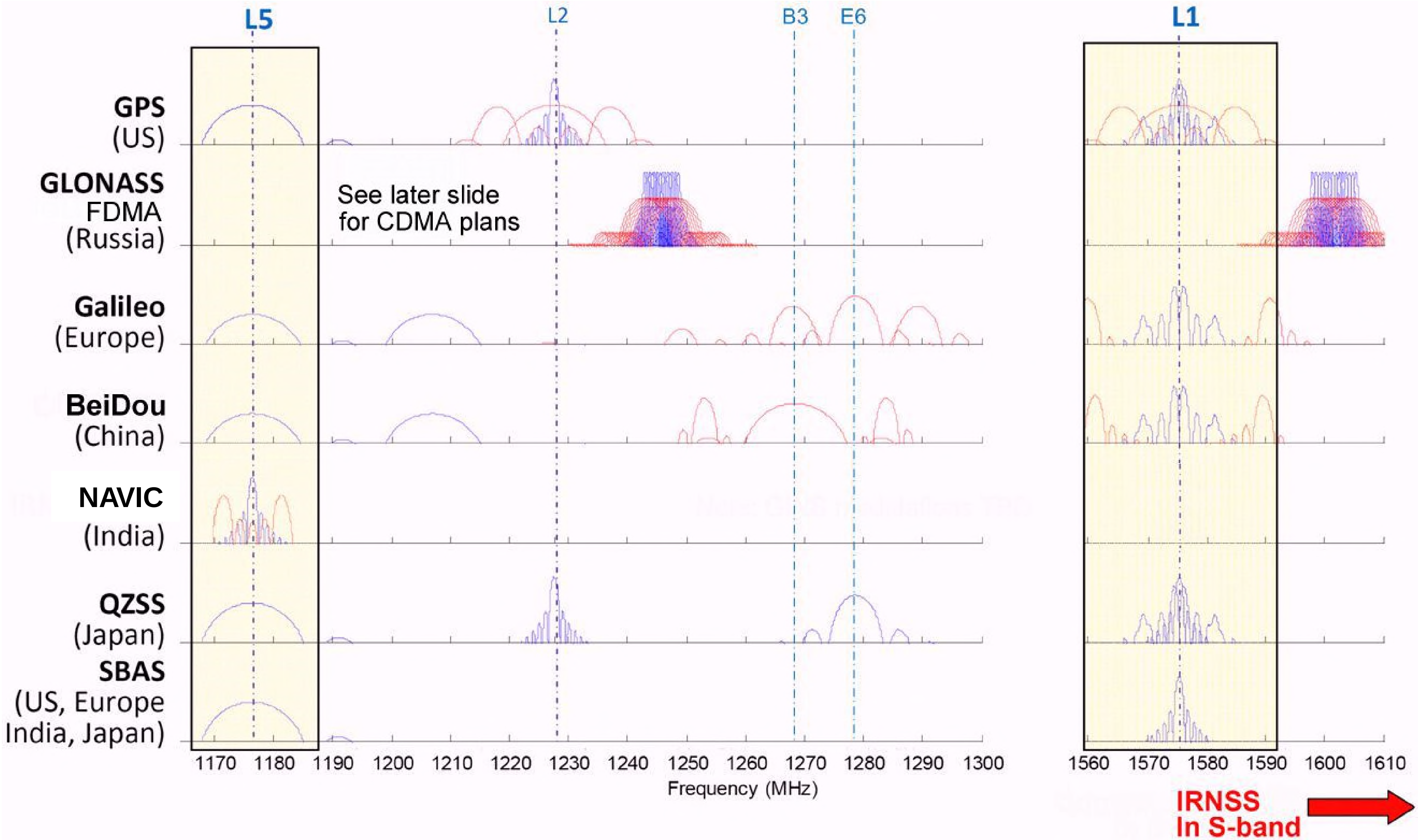
Main Benefits of Interoperability

More Satellites ➔ Better Geometry ➔ Improves:

- **Satellite coverage**
  - ➔ Navigate where could not before
- **Dilution of Precision**
  - ➔ Accuracy is better everywhere
  - ➔ Eliminates DOP holes (with open sky)
- **RAIM***
  - ➔ Integrity checked everywhere, all the time
  - ➔ Eliminates RAIM holes (with open sky)
- **Phase ambiguity resolution**
  - ➔ For survey and machine control applications
- **Accuracy**
  - ➔ Allows higher elevation angle cutoff which reduces multipath, ionospheric, and tropospheric errors

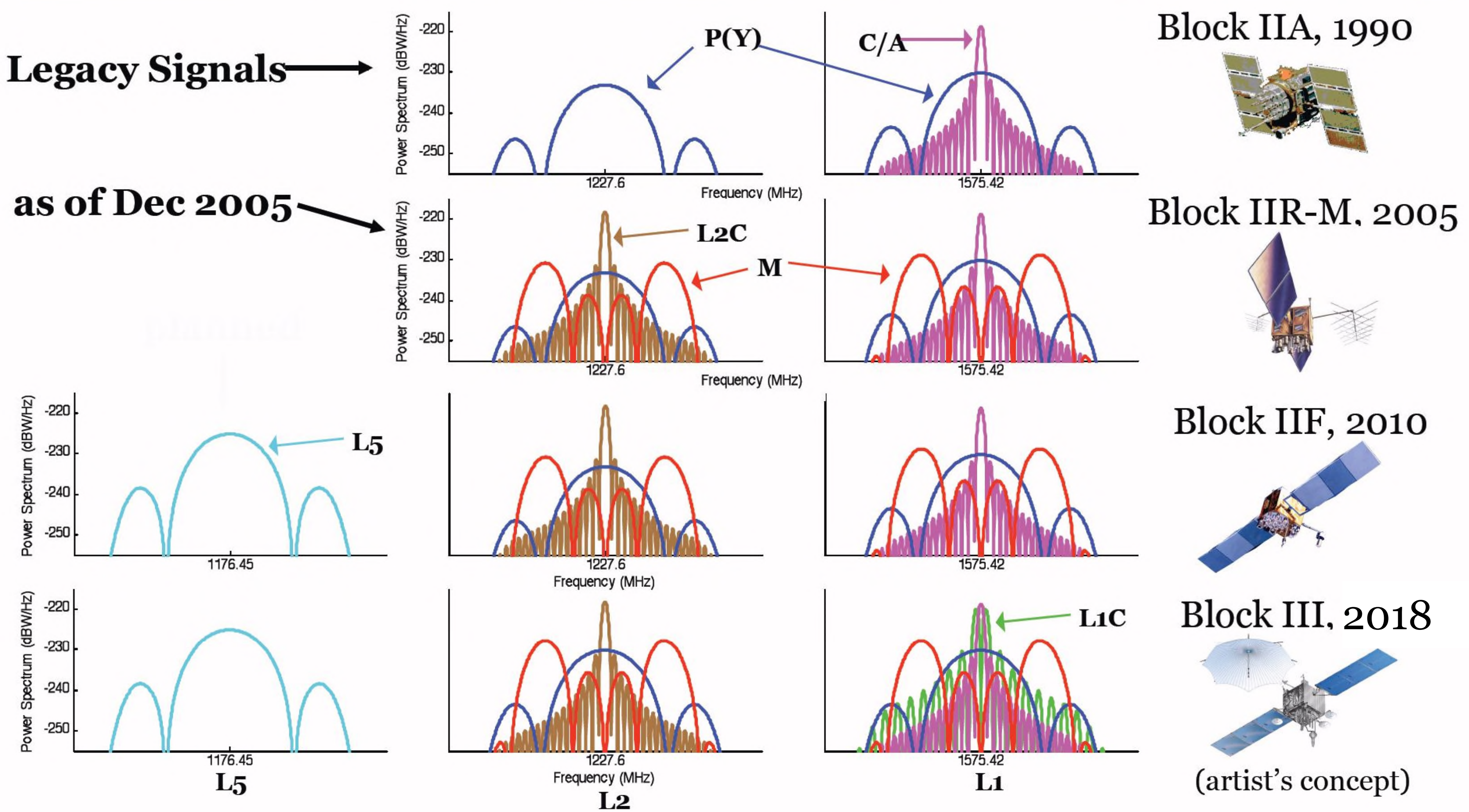
* Receiver Autonomous Integrity Monitoring

Spectrum of GNSS Signals



GPS Signals

GPS Signals (Cont'd)



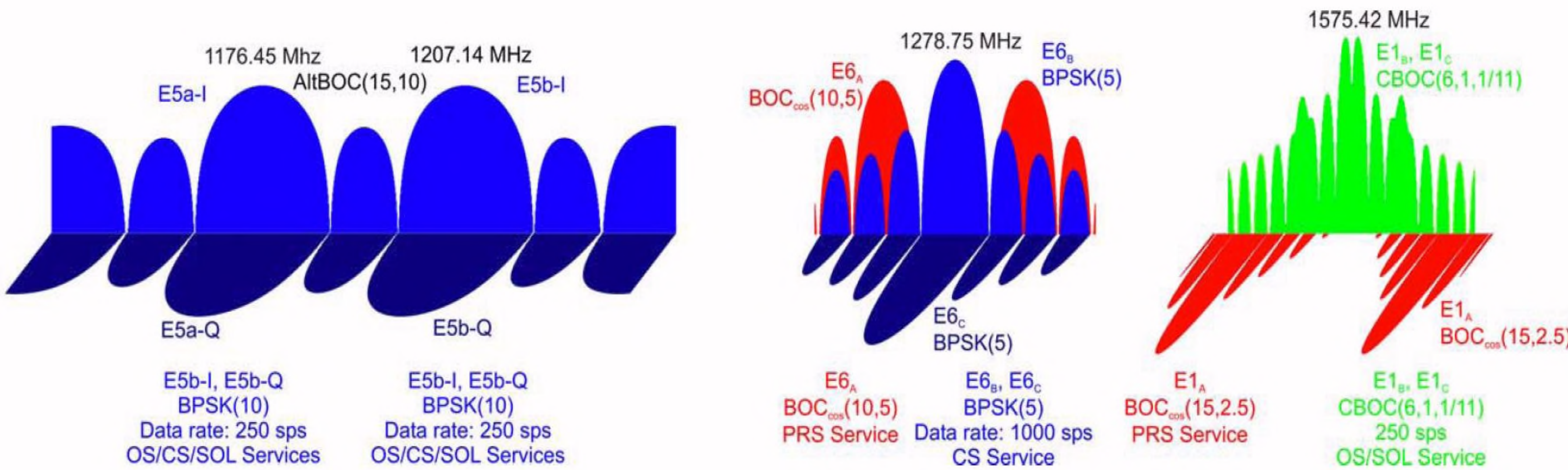
Originally presented December 2008; Updated to current status and plans

GPS Signals Summary

Band	Center Frequency	Signal	Waveform	Notes
L1	1575.42 MHz	C/A	BPSK(1)	Open Service
		P(Y)	BPSK(10)	
		L1C	TMBOC	Open Service, Separate Pilot and Data Channels
		M	BOC(10,5)	
L2	1227.6 MHz	P(Y)	BPSK(10)	
		L2C	BPSK(1)	Open Service, Separate Pilot and Data Channels
		M	BOC(10,5)	
L5	1176.45 MHz	L5	BPSK(10)	Open Service, Separate Pilot and Data Channels

Galileo Signals

Galileo Signal Baseline



- **E5: AltBOC(15,10) – 2 x BPSK(10)**
- **E6: BPSK(5) and $BOC_{cos}(10,5)$**
- **E1: MBOC(6,1,1/11) and $BOC_{cos}(15,2.5)$**
  - **Latest joint EU/US decision to implement MBOC in 2007**

Institute of Geodesy and Navigation
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Galileo Signals Summary

Band	Center Frequency	Signals	Waveform	Notes
E1	1575.42 MHz	E1 OS	CBOC	Open Service, Separate Pilot and Data Channels
		PRS	BOC(15,2.5)	
E6	1278.75 MHz	CS	BPSK(5)	Commercial Service, Separate Pilot and Data Channels
		PRS	BOC(10,5)	
E5	1191.795 MHz	E5a & E5b	AltBOC(15,10)	Open Service, Separate Pilot and Data Channels

QZSS Signals

QZSS Service

QZSS Signals

Note: Some signal changes are being evaluated

	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

GLONASS

Signal Plans

GLONASS Modernization

РОСКОСМОС

1982	2003	2011	2014

"Glonass"

- 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"

- 7 year design life
- Clock stability $1*10^{-13}$
- Signals: Glonass + L2OF (FDMA)
- Totally launched 36 satellites
- Another 12 satellites ordered

"Glonass-K1"

- 10 year design life
- Unpressurized bus
- Expected clock stability $\sim 10\ldots5*10^{-14}$
- Signals: Glonass-M + L3OC (CDMA) – test
- SAR

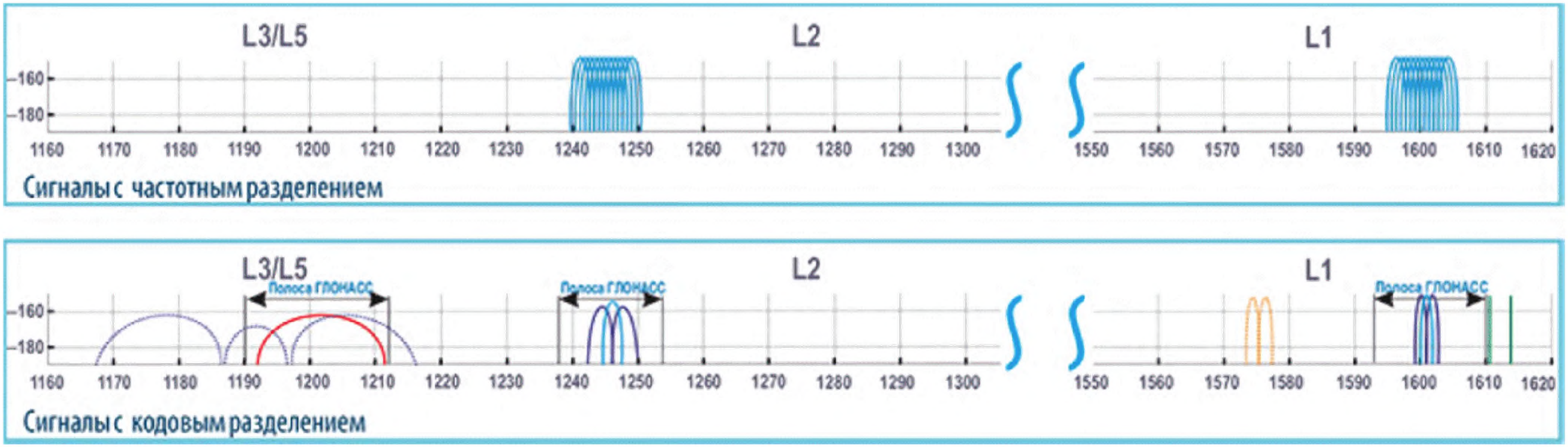
"Glonass-K2"

- 10 year design life
- Unpressurized
- Expected clock stability $\sim 5\ldots1*10^{-14}$
- Signals: Glonass-M + full set of CDMA signals
- SAR

CDMA signals general structure already designed

Future GLONASS Signal Spectrum

THE SPECTRUM OF NAVIGATION RADIO SIGNALS OF THE GLONASS SYSTEM



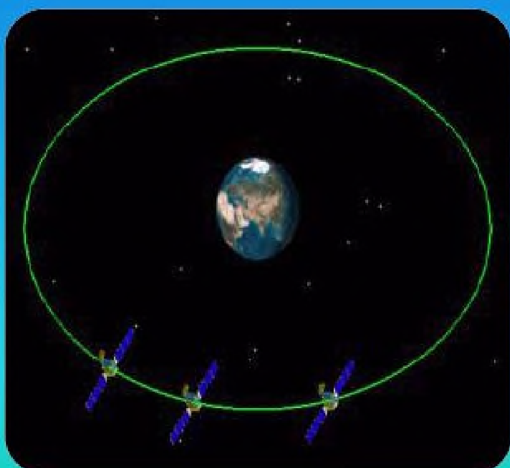
CHARACTERISTICS OF NAVIGATION RADIO SIGNALS OF THE GLONASS SYSTEM WITH CODE DIVISION

Range	Carrier frequency, MHz	Signal	Code length , symbols	Clock frequency, MHz	Modulation type	Transmission speed CI, bit / s
L1	1 600,995	L1OCd L1OCp	1 023 4 092	1,023 1,023	BPSK (1) BOC (1.1)	125 pilot signal
L2	1 248.06	L2 CSI L2OCp	1 023 4 092	1,023 1,023	BPSK (1) BOC (1.1)	250 pilot signal
L3	1 202,025	L3OCd L3OCp	10 230 10 230	10.23 10.23	BPSK (10) BPSK (10)	100 pilot

BeiDou
Signal Plans
(From Several Presentations)

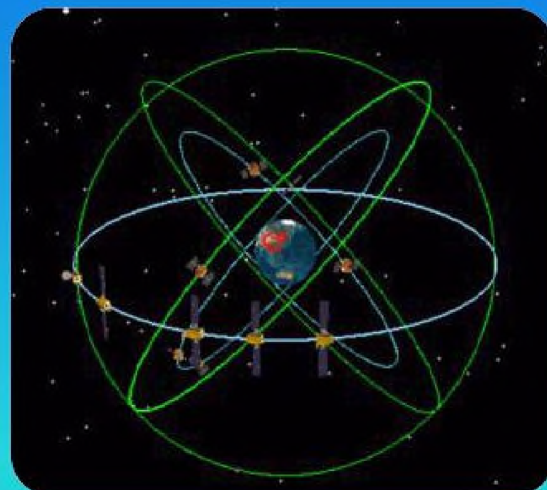
2. Development Plan

1st Step



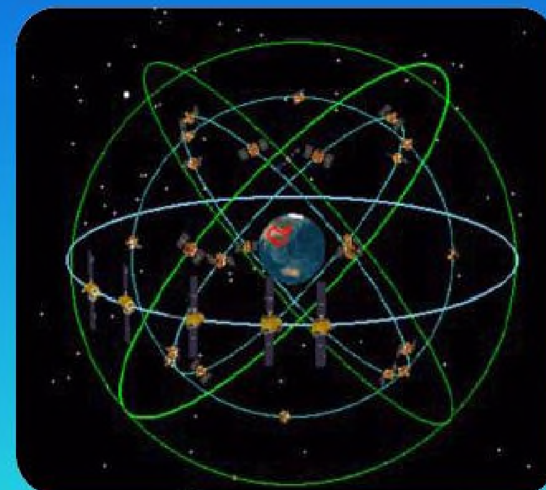
BeiDou Demonstration System

2nd Step



BeiDou Navigation Satellite System

3rd Step



BeiDou Navigation Satellite System

1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 2020

Signal Characteristics

- Frequencies

B1: 1559.052~1591.788MHz

B2: 1166.22~1217.37MHz

B3: 1250.618~1286.423MHz

Till the year	Constellation	Signals (actual emission)
2012	**5GEO+5IGSO+4MEO （Regional Service）**	**mainly COMPASS Phase(CP) II signals**
2020	**5GEO+3IGSO+27MEO （Global Service）**	**mainly CP III signals**

Signal Characteristics

- *CP II: B1, B2, and B3 as below*

Component	Carrier Frequency (MHz)	Chip Rate (cps)	Bandwidth (MHz)	Modulation Type	Service Type
B1(I)	1561.098	2.046	4.092	QPSK	Open
B1(Q)		2.046			Authorized
B2(I)	1207.14	2.046	24	QPSK	Open
B2(Q)		10.23			Authorized
B3	1268.52	10.23	24	QPSK	Authorized

◆CP III: B1, B2 and B3 as below

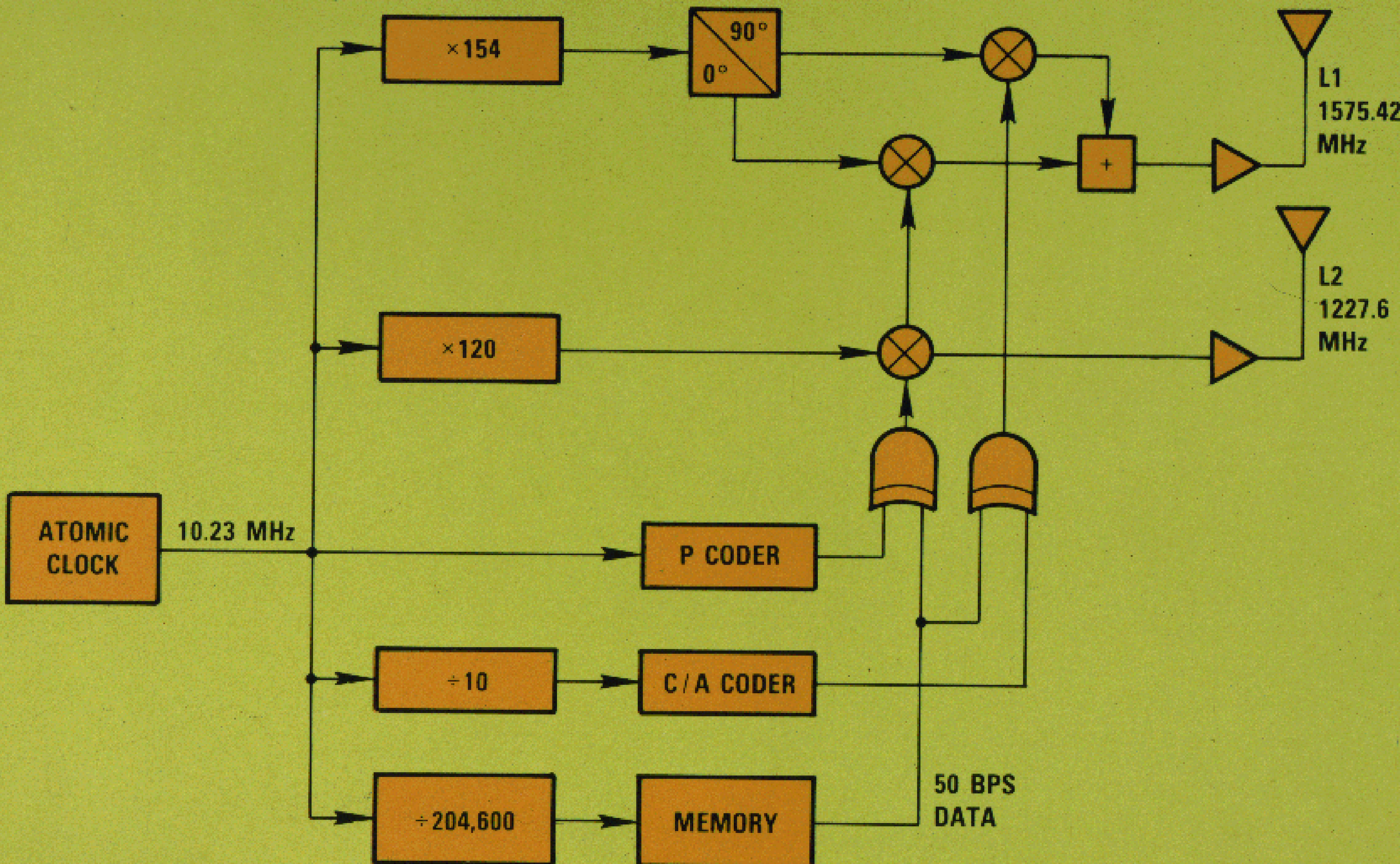
Component	Carrier Frequency (MHz)	Chip Rate (cps)	Data/Symbol Rate (bps/sps)	Modulation Type	Service Type
B1-C_D	1575.42	1.023	50/100	MBOC(6,1,1/11) “QBOC”	Open
B1-C_P			No		
B1-A		2.046	50/100	BOC（14，2）	Authorized
			No		
B2a_D	1191.795	10.23	25/50	AltBOC(15,10)	Open
B2a_P			No		
B2b_D			50/100		
B2b_P			No		
B3	1268.52	10.23	500bps	QPSK(10)	Authorized
B3-A_D		2.5575	50/100	BOC(15,2.5)	Authorized
B3-A_P			No		

International Committee on
Global Navigation Satellite Systems

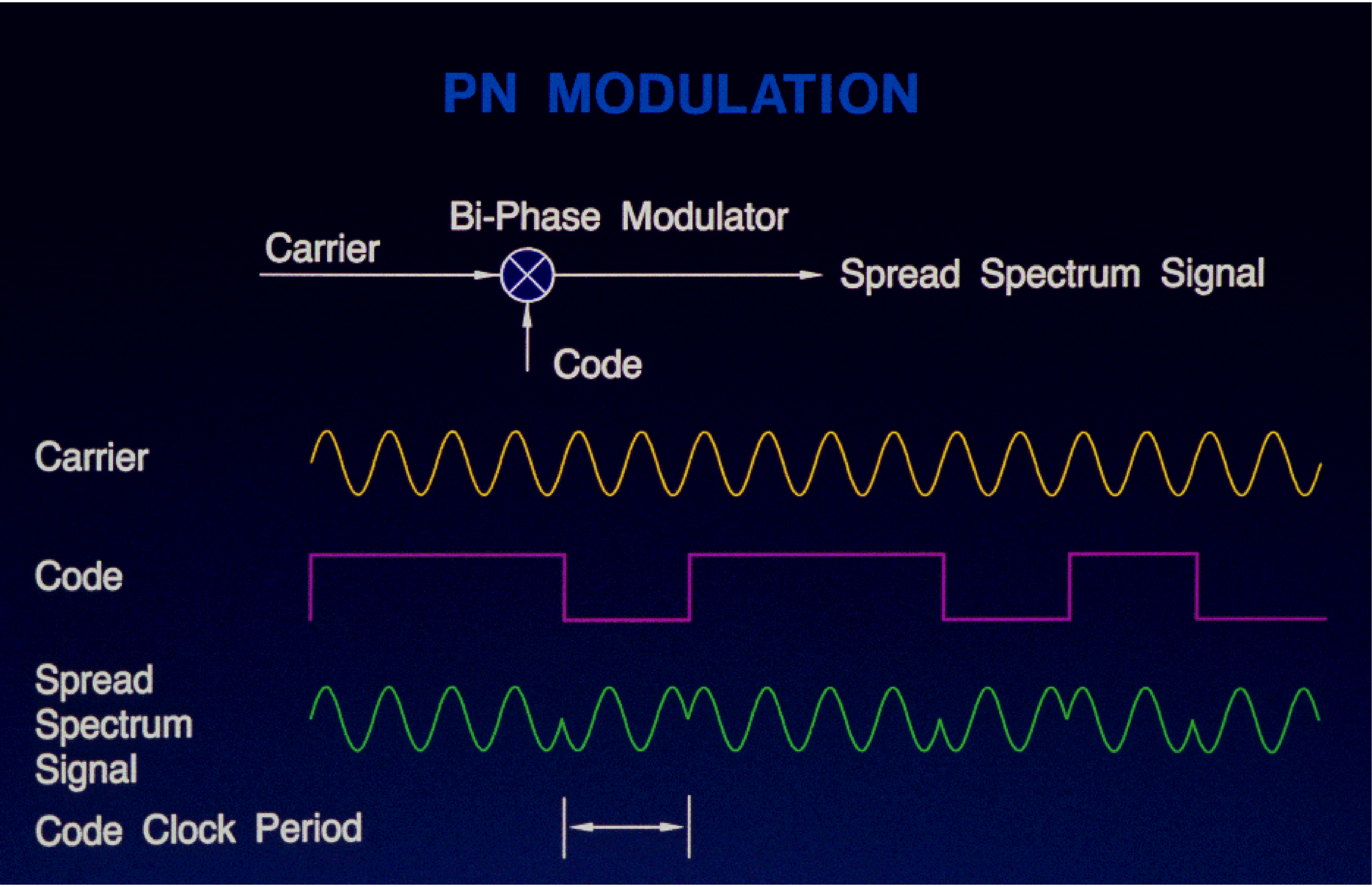
GNSS Signals, Spectra, and Receiver Fundamentals

Magnavox

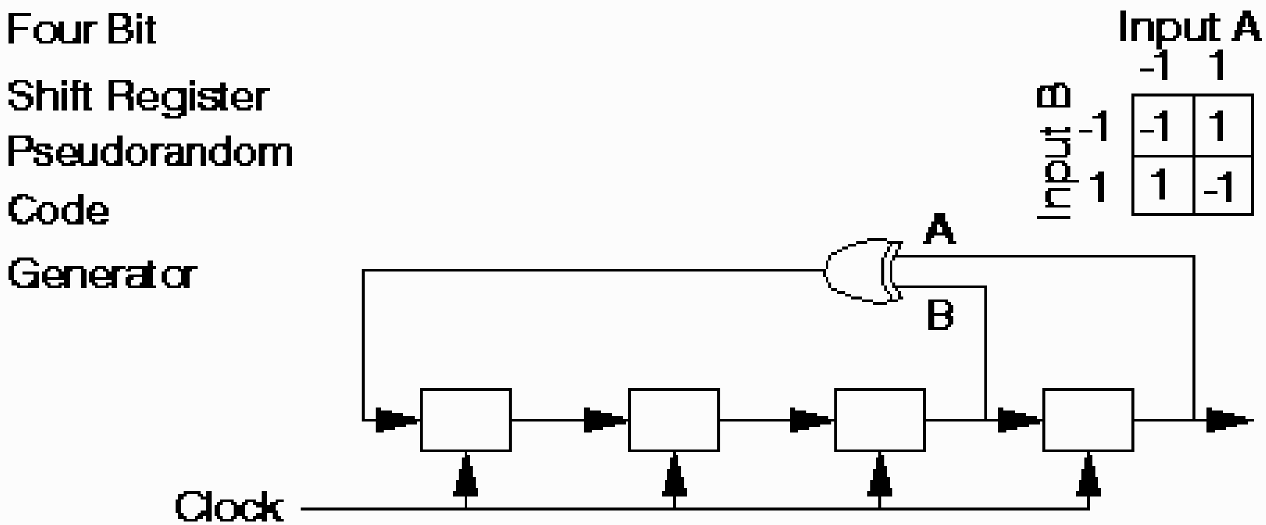
SIMPLIFIED GPS SATELLITE BLOCK DIAGRAM



1188-3311


PN MODULATION
Bi-Phase Modulator
Carrier
Spread Spectrum Signal
Code
Carrier
Code
Spread
Spectrum
Signal
Code Clock Period

Simple Pseudorandom Code Generator

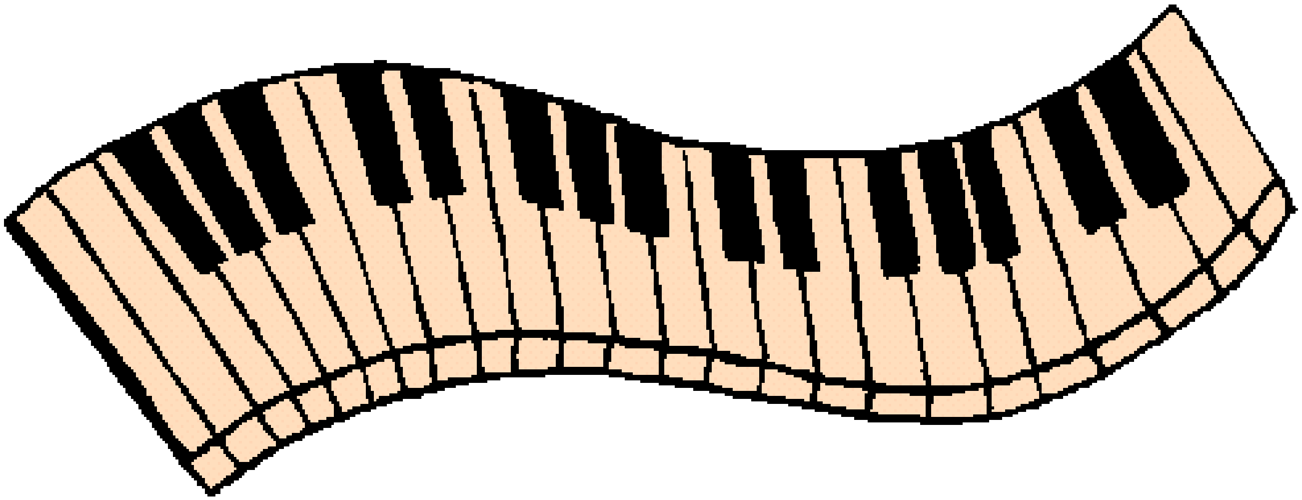


1	1	1	1
-1	1	1	1
-1	-1	1	1
-1	-1	-1	1
1	-1	-1	-1
-1	1	-1	-1
-1	-1	1	-1
1	-1	-1	1
1	1	-1	-1
-1	1	1	-1
1	-1	1	1
-1	1	-1	1
1	-1	1	-1
1	1	-1	1
1	1	1	-1
1	1	1	1

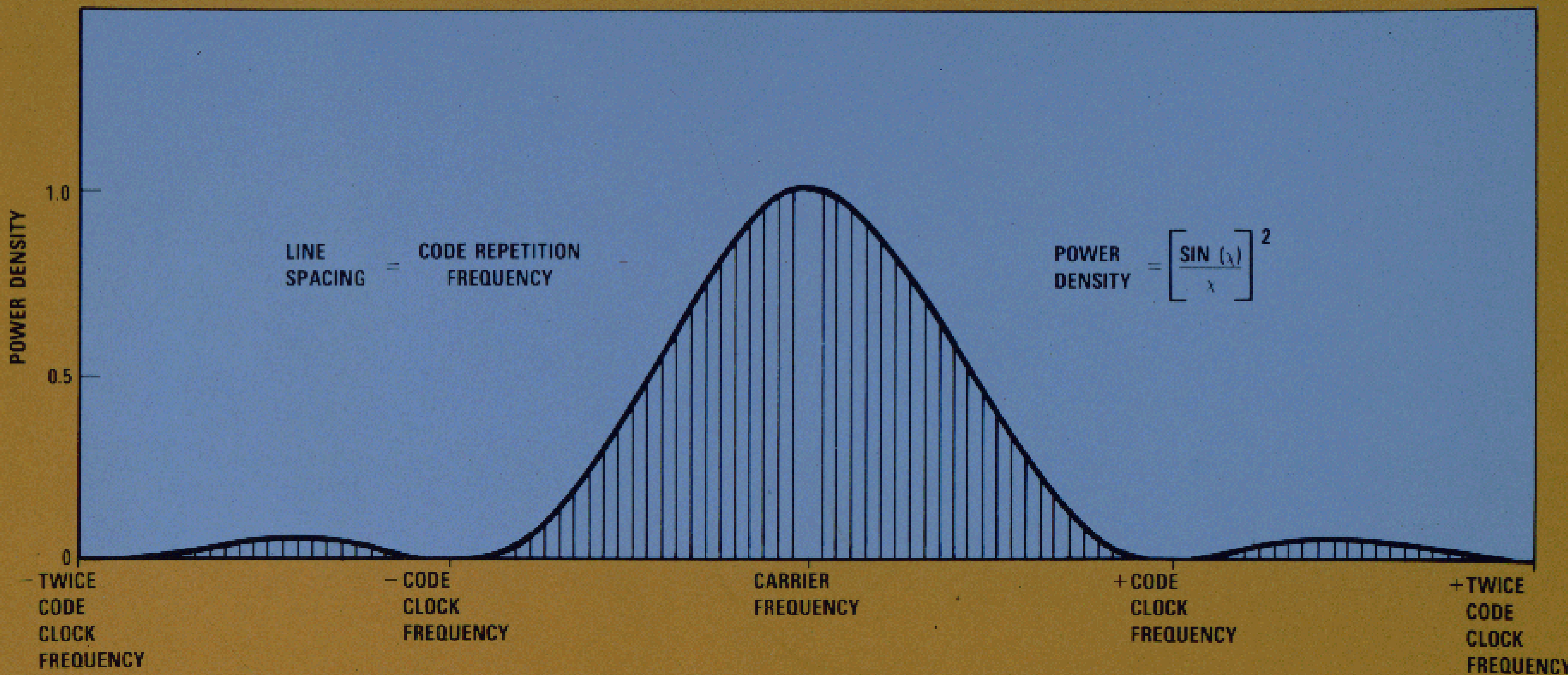
Code length =
$(2^N - 1)$ =
$(2^4 - 1) = 15$

C/A Code length =
$(2^N - 1)$ =
$(2^{10} - 1) = 1023$

Code Modulation Spreads the Spectrum



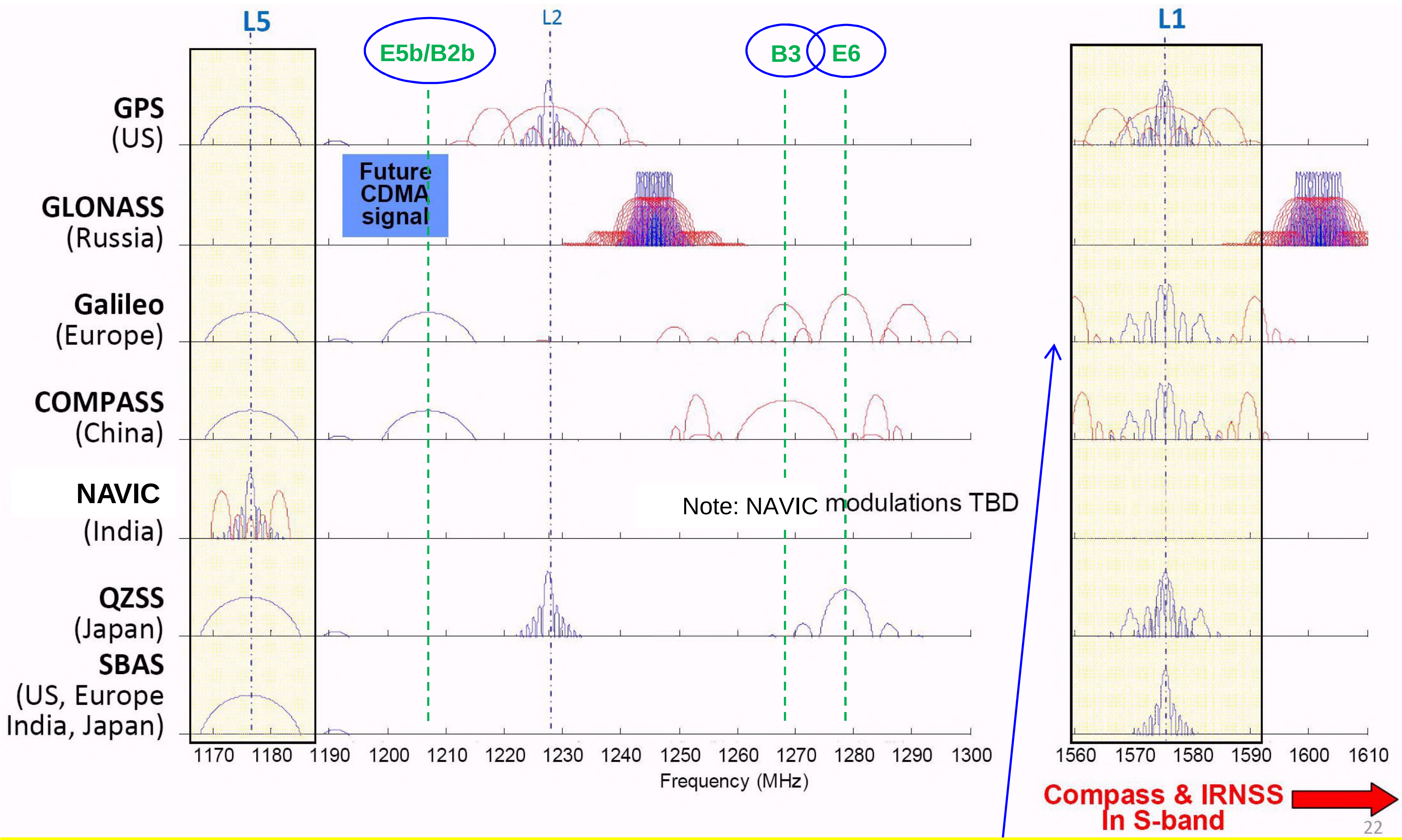
SPREAD SPECTRUM POWER DENSITY



Frequency Domain

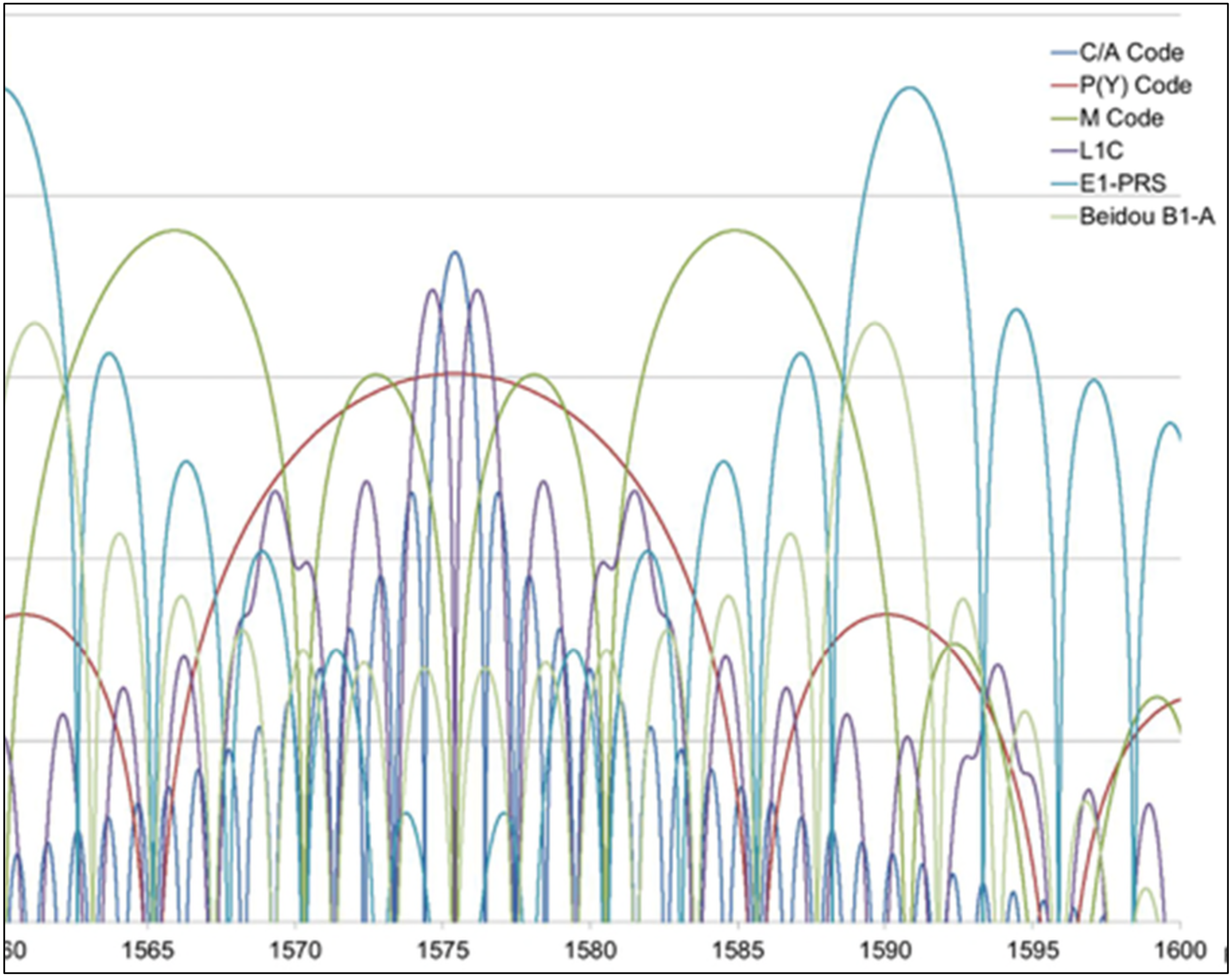
1188-3313

GNSS Spectra



L1, L2, & L5 are paramount, but also GLONASS, PRS, E5b, B3, & E6

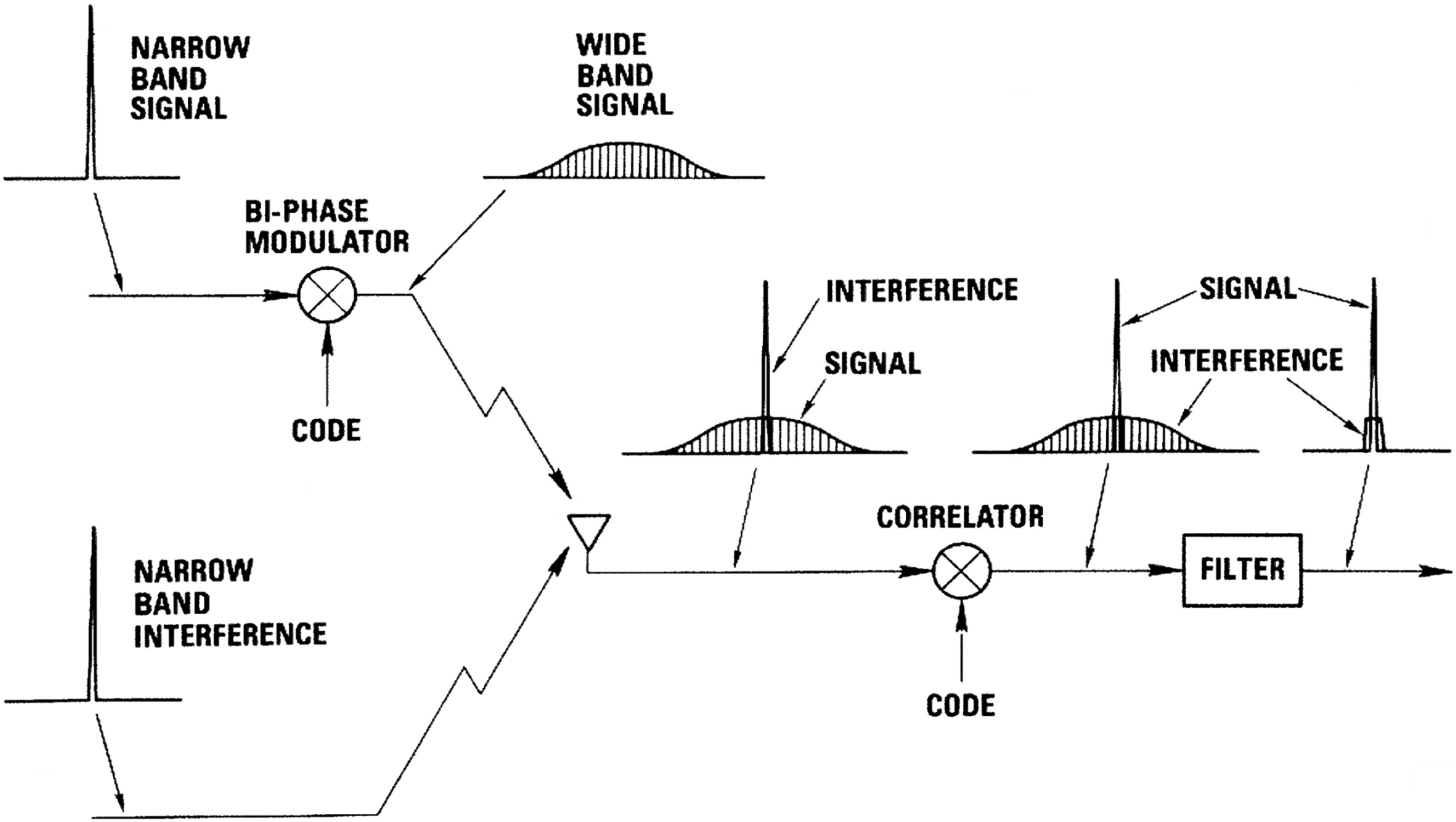
GNSS L1 Spectrum



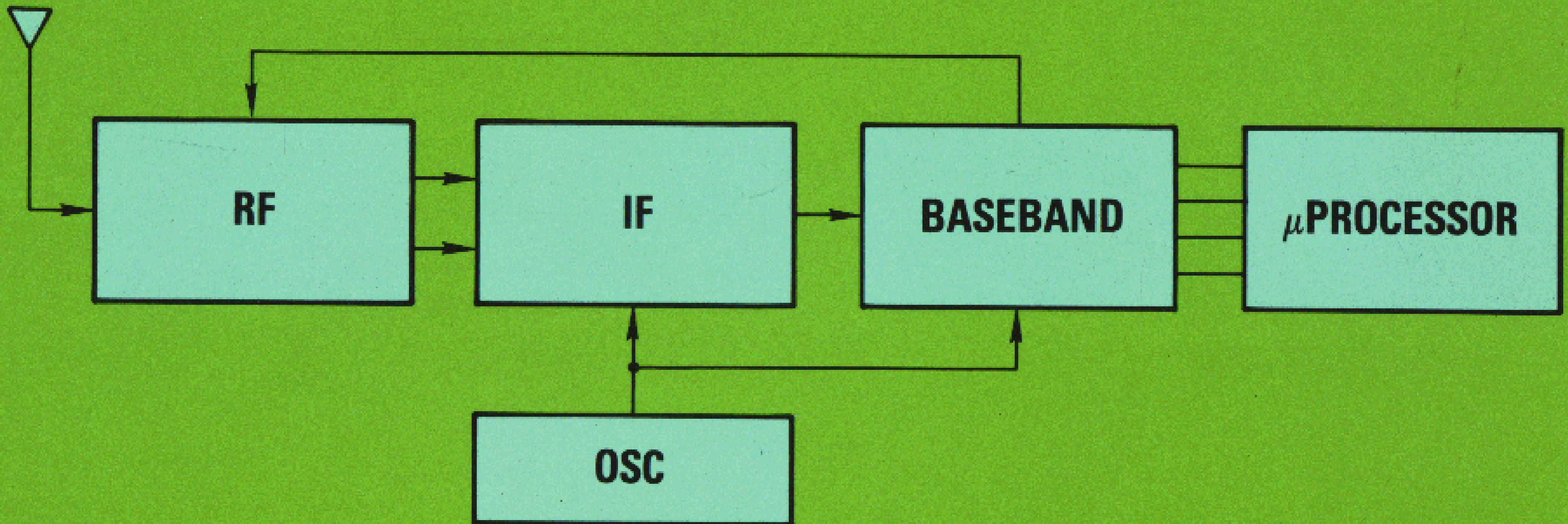
Power Spectral Density (dBW/MHz)

Frequency (MHz)

Receiver Signal Processing



CORE GPS CHIP SET



388-680

27 Years with Just 3 GPS Signals

Signal/SV	IIR			
L1 C/A	✓			
L1 P(Y)	✓			
L1 M				
L1C				
L2 P(Y)	✓			
L2C				
L2 M				
L5				

Direct civil access to C/A code

Indirect civil access by codeless and semi-codeless means

1978 to 2005

IIR-M Satellites Added Three More

Signal/SV	IIR	IIR-M		
L1 C/A	✔	✔		
L1 P(Y)	✔	✔		
L1 M		✔		
L1C				
L2 P(Y)	✔	✔		
L2C		✔		
L2 M		✔		
L5				

Direct civil access to L2C code

1978 to 2005

2005

IIF Satellites Added L5

Signal/SV	IIR	IIR-M	IIF
L1 C/A	✔	✔	✔
L1 P(Y)	✔	✔	✔
L1 M		✔	✔
L1C			
L2 P(Y)	✔	✔	✔
L2C		✔	✔
L2 M		✔	✔
L5			✔
	1978 to 2005	2005	2010

Safety service in ARNS band

GPS III Will Add L1C

Signal/SV	IIR	IIR-M	IIF	III
L1 C/A	✓	✓	✓	✓
L1 P(Y)	✓	✓	✓	✓
L1 M		✓	✓	✓
L1C				✓
L2 P(Y)	✓	✓	✓	✓
L2C		✓	✓	✓
L2 M		✓	✓	✓
L5			✓	✓
	1978 to 2005	2005	2010	2018?

Better performance

Modernized Signal Structures

- The most important improvements in GNSS signal structures since1978 have been adopted for essentially every new and modernized signal
  - Including GPS, Galileo, BeiDou, and QZSS
  - Hopefully also for NAVIC and GLONASS CDMA
- The improvements are (a) to have a data-less pilot carrier and (b) to use Forward Error Control (FEC) to enhance data reception
- There are many other variations, e.g.,
  - Binary Offset Carrier (BOC) combinations, spreading code structures, FEC techniques, power split between data and pilot channels, symbol interleaving, etc.
  - Each has a purpose, e.g., spectrum separation

Signal Structure, Interoperability, and Geometry

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23 January 2018
ICG Workshop, Bangkok, Thailand

Disclaimer

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The Most Important Ingredient

- Only Navigation by Satellite can provide **excellent Geometry**
  - *Continuous, worldwide, four dimensional, with excellent accuracy*
  - *GDOP, Geometric Dilution of Precision, and its important children:*
    - PDOP, HDOP, VDOP, and TDOP
  - *Although the satellite signals may be weak, the geometry is strong*
- No <u>terrestrial</u> navigation aid delivers "the most important ingredient"
- Do users need better geometry than GPS alone can provide?
- The answer is a definite "YES" as demonstrated by:
  - *Widespread use of GLONASS in products from consumer mobile phones to commercial survey and machine control products*
    - In spite of the difficulty of using GLONASS FDMA with GPS CDMA
  - *Plus widespread development of receivers to use <u>all</u> available GNSS*
- Aircraft at altitude and ships at sea may not <u>need</u> more than GPS
  - *But integrity by A-RAIM requires many more satellites*
- Users subject to signal blockage or outage do need more satellites
- Thus, the second most important ingredient is signal interoperability
  - *<u>Enabling</u> the best geometry by using every interoperable satellite signal*

Signal Structure and Interoperability Considerations

- Interoperability is in the eye of the beholder
- For example, L1C and E1 OS have identical center frequencies and identical spectra, but almost everything else is different

Signal	Spreading Code Length (chips)	Spreading Code Duration	Modulation	Channel with BOC(6,1)	Data Power Percent	Pilot Power Percent	Symbol Rate	Bit Rate	Forward Error Correction	Pilot Overlay Code Duration	Message Frame Length
L1C	10,230	10 ms	TMBOC	Pilot	25%	75%	100 SPS	50 BPS	LDPC	18 sec	18 sec
E1 OS	4,092	4 ms	CBOC	Both	50%	50%	250 SPS	125 BPS	Convolutional	100 ms	720 sec

- Receivers will handle the differences and hide them from the user
  - *The user will experience better performance due to more satellites*
- However, different types of receivers will take advantage of some of the signal differences between systems
  - *Identical center frequency is important for high precision receivers and for bandwidth limited GNSS antennas on aircraft*
  - *Many receivers will use GPS L1 C/A for fast signal acquisition but the other signal structures for navigation, positioning, and timing*

Predicting the Future

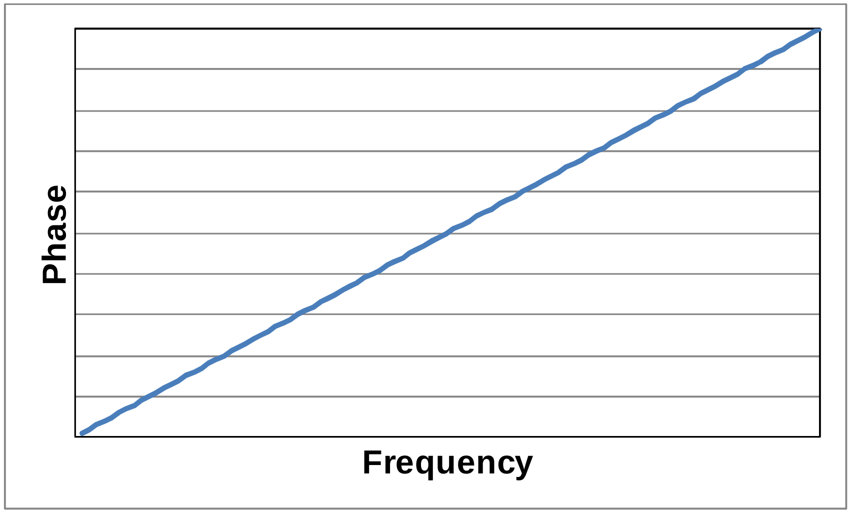
- If there are three global interoperable GNSS constellations in 2020
  - *GPS, Galileo, and BeiDou, with a total of 72 to 90 operational satellites*

1. Use of GLONASS FDMA will decrease for precision applications
   - *The current demand for more satellites will be satisfied by interoperable CDMA signals, leaving little demand for the more difficult FDMA signals*
2. Users will not say “this is my GNSS” or “this is my BeiDou”
   - *There will be few <u>if any</u> GPS-only or BeiDou-only or Galileo-only receivers*
   - *Users won’t know and they won’t care where the signals originate*
   - *They will just enjoy the better performance provided by better geometry*
   - *And they probably will continue to call their device a “GPS” (sorry!)*
3. Special, unique, or “orphan” signals will be little used
   - *Use of GPS L2C will decline because no other GNSS provides it*
   - *The standard dual-frequency pair will become 1575.42 and 1176.45 MHz*
   - *E5b and B2b will be little used, whereas E5a and B2a will be widely used*
     - A lively discussion topic!

Future Decrease in High Precision FDMA Use

- A pure “time delay” Δt is characterized by a linear slope of phase versus frequency

$$\Delta\varphi / \Delta f = \Delta\varphi / (\Delta\varphi / \Delta t) = \Delta t$$



- However, a bandpass filter must rapidly attenuate signals outside the bandpass region
- This introduces nonlinearities in phase versus frequency, especially at the band edges
- In high precision applications it is desirable for every signal from every satellite to experience the same nonlinearities so there are no time delay differences between signals due to receiver filtering
- This will be true if every signal has the same center frequency
- Because this is not true for GLONASS FDMA signals, very careful calibration of each channel is required for near-precision results
- This is why high precision use of GLONASS FDMA will likely decrease substantially with deployment of Galileo and BeiDou

AEROSPACE

Growth Continues and Should Accelerate

- Application growth is fueled primarily by the private sector
  - *Heavily regulated products, e.g., for aviation and the military, are slow to change and generally lag in innovation (sad but true)*
- Factors that encourage innovation and application growth:
  - *Competition, Moore's law, opportunity, fear, and the profit motive*
- What in the future will stimulate growth:
  - *Much better GNSS geometry improves availability, continuity, integrity, and accuracy, especially in difficult environments*
    - Urban canyons, real canyons, open pit mining, even aviation
  - *A-RAIM will become practical and begin to displace SBAS use*
  - *Ambiguity resolution for Real Time Kinematic (RTK) in survey and machine control will become almost instantaneous and more reliable*
    - Improved vertical accuracy will displace some laser plane requirements
- Alternate means to communicate message parameters will promote "instant navigation" for all applications (push to navigate)