Stanford's 2014 PNT Symposium

New Signal Structures
for
BeiDou Navigation Satellite System

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Outline

1 Background and Motivation

2 Requirements and Challenges

3 New Signal Structures for BeiDou

4 Some Test Results

5 Summary

1 Background and Motivation

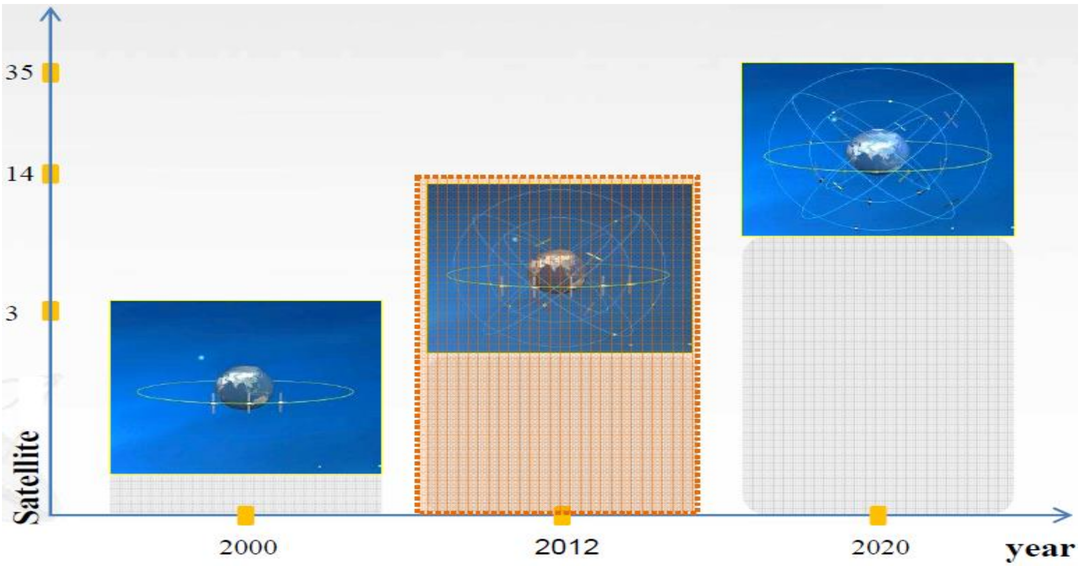
- Development of GNSS worldwide
  - Modernization of existing systems: GPS, GLONASS
  - Construction of emerging systems: Galileo, BeiDou
  - Development of regional systems: QZSS, IRNSS

1 Background and Motivation

- BeiDou Navigation Satellite System
  - First Step: BeiDou Phase I, 2000~2012
    - Experimental system
    - SVs: 3 GEO satellites
    - Signals: L+S
    - Coverage: regional (China and its surrounding areas)
    - Status: closed
  - Second Step: BeiDou Phase II, by 2012
    - Regional System
    - SVs: 14 satellites in orbit (5GEO+5IGSO+4MEO)
    - Signal: B1, B2, B3
    - Coverage: regional (China and its surrounding areas)
    - Status: FOC

1 Background and Motivation

- BeiDou Navigation Satellite System (continued)
  - Third Step: BeiDou Phase III, by 2020
    - Global System
    - SVs: 35 satellites (5GEO+30nonGEO)
    - Signals: New B1, B2, B3
    - Coverage: global
    - Status: under construction



1 Background and Motivation

- Existing BeiDou Phase II Signals
  - Two services: authorized service and open service
  - Two open service signals： B1(I), B2(I)
    - BPSK(2), 2.046Mcps
    - Orthogonal to B1(Q), B2(Q) respectively
    - The ICD of B1I and B2I released in 2012, 2013

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

1 Background and Motivation

- Signal Design for BeiDou Phase III
  - The design of open service signal is the one of a series of challenges in BeiDou global system construction.
  - In the past years, signal design aroused wide attention from academia and industry in China, and a number of research results has achieved.

Outline

2.1 Planned BeiDou Signals

- New Signals of BeiDou Phase III in the Plan
  - Two different services will be provided: authorized service and open service
  - At least two distinct signals for open service will be deployed in L band: new B1 and new B2
  - New open service signals in the plan
    - B1C: 1575.42MHz (L1/E1)
    - B2: B2a 1176.45 MHz (L5/E5a), B2b 1207.14 MHz (E5b)

2.1 Plannd BeiDou Signals

Early Signal Proposed BeiDou Phase III

Component	Carrier (MHz)	Chip rate (cps)	Data/Symbol rate (bps/sps)	Modulation	Service
B1-C$_D$	1575.42	1.023	50/100	**MBOC(6,1,1/11)**	**Open**
B1-C$_P$			No		
B1		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**		

[1] China Satellite Navigation Office, BeiDou Navigation Satellite System, The 5th Meeting of International Committee on GNSS, 2010

2.1 Planned BeiDou Signals

- Main drawback in early proposed BeiDou signals
  - No independent intellectual property rights, big patent risk
  - Signalsôperformance need to be improved
  - More flexible receiving modes and more varied application scenarios need to be considered

2.2 Requirements of BeiDou Signals

- Main requirements of BeiDou open service signals
  - Independent intellectual property rights
  - Better compatibility and interoperability
  - Smooth transition from Phase II to Phase III
  - Improved performance
  - é é

2.2 Requirements of BeiDou Signals

- Some requirements for B1C signal
  - Compatibility with other signals of the same carrier frequency
  - Better interoperability with GPS L1 and Galileo E1 signals
  - Better ranging accuracy (than GPS C/A and BeiDou Phase II B1(I))
  - Receiving mode diversity for different receivers (low-end, high-end)
  - Independent Intellectual property rights
  - é é

2.2 Requirements of BeiDou Signals

- Some requirements for B2 signal
  - Multiplexed B2a and B2b into a constant envelope signal
  - Better interoperability with the GPS L5 and GALILEO E5
  - High ranging accuracy
  - In-band interference-resistant ability (MAI, DME, TACAN, near-far effect, etc.)
  - joint optimization with B1C
  - Independent intellectual property rights
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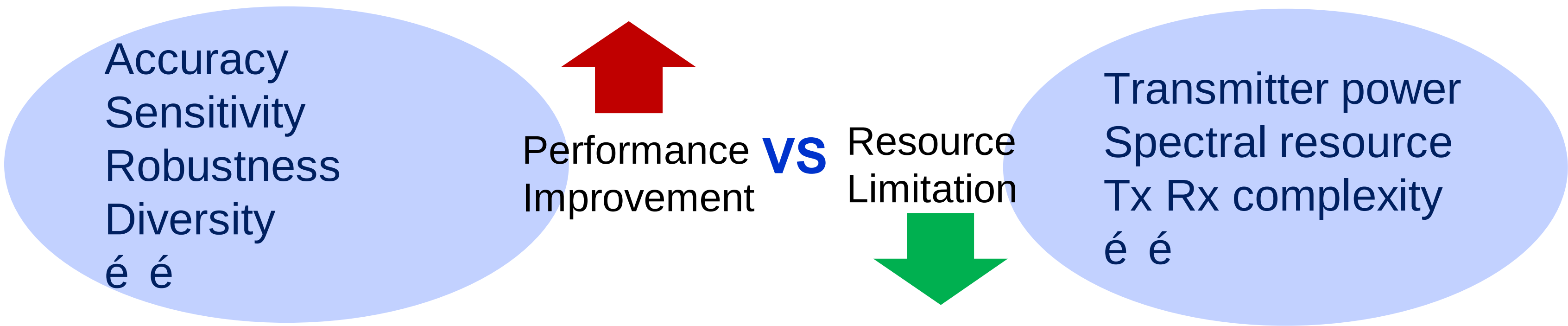
2.3 Challenges in GNSS Signal Design

Main Challenges in GNSS Signal Design

The primary contradiction between performance improvement vs resource limitation



Additional Challenges

- coexistence of legacy and new signals / smooth transition form Phase II to Phase III
- compatibility and interoperability across multiple systems
- é é

Outline

1 Background and Motivation

2 Requirements and Challenges

3 New Signal Structures for BeiDou

3.1 Quadrature Multiplexed BOC

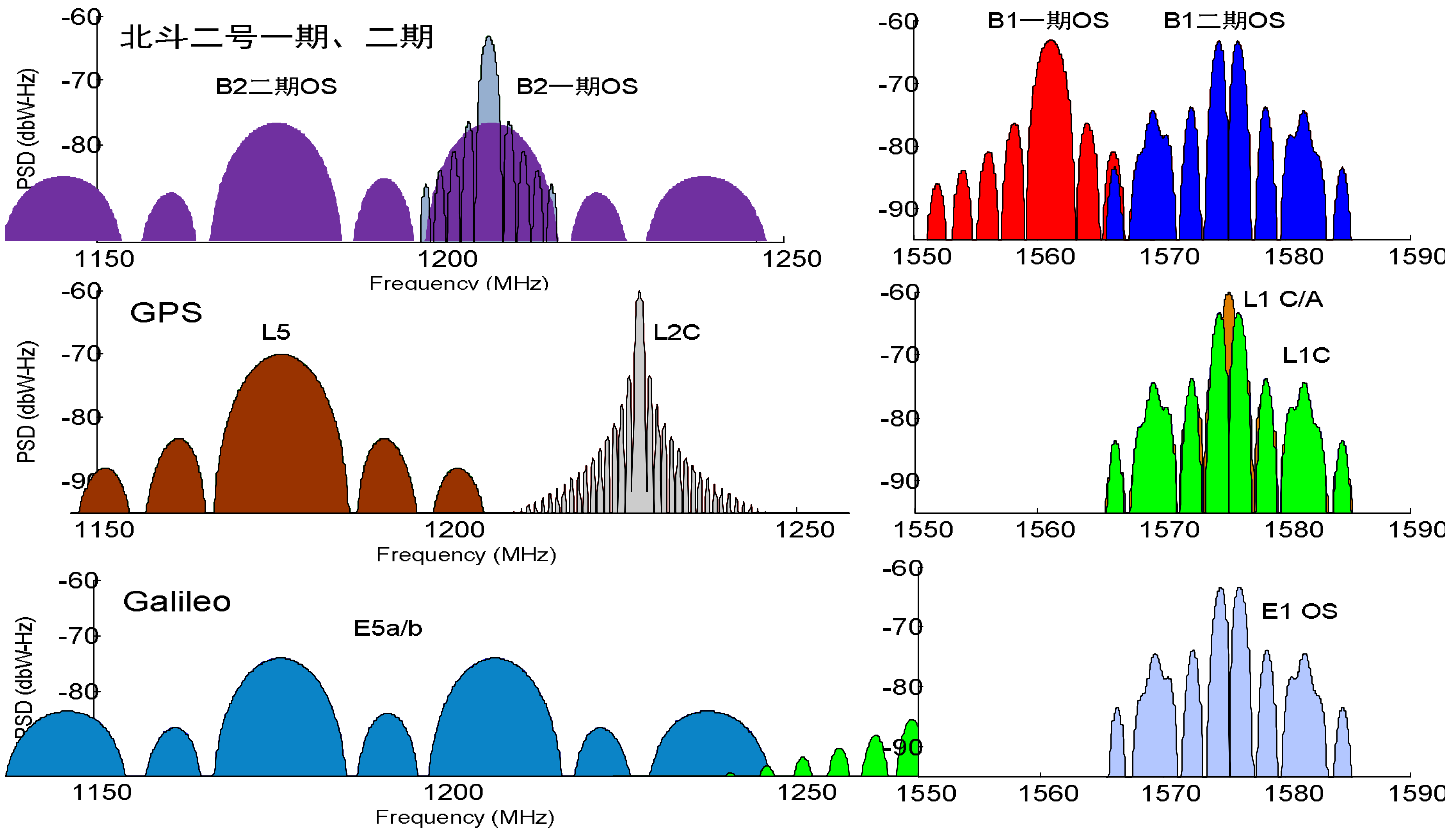
3.2 Asymmetric Constant Envelope BOC

4 Some Test Results

5 Summary

3 Progress in BeiDou Signal Design

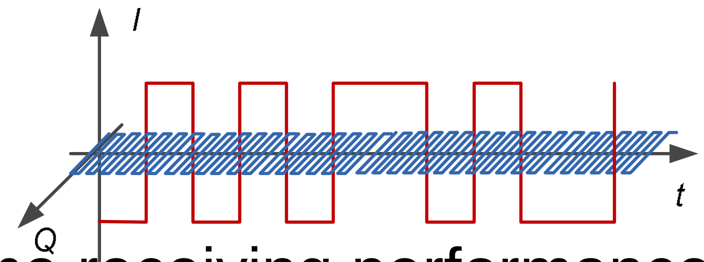
- New Candidates Proposed for B1, B2
  - QMBOC -- Quadrature Multiplexed BOC
  - ACE-BOC--Asymmetric Constant Envelope BOC



3.1 Quadrature Multiplexed BOC

- QMBOC -- Quadrature Multiplexed BOC
- Dedicated for interoperable signal in B1
- BOC(1,1) and BOC(6,1) are modulated on two quadrature phases, with same PRN code or different PRN codes

$$s_d(t) = c_d(t) d(t) s_{\mathrm{QMBOC}}(t)$$
$$= \sqrt{1-\gamma} c_d(t) d(t) s_{\mathrm{BOC}(n,n)}(t) \pm j\sqrt{\gamma} c_d(t) d(t) s_{\mathrm{BOC}(m,n)}(t)$$



  - Have the same receiving performance as TMBOC and CBOC, while avoiding MBOC patent risk

[1] Zheng Yao, Mingquan Lu, and Zhenming Feng, Quadrature multiplexed BOC modulation for interoperable GNSS signals, *Electronics Letters*, 2010, 46(17): 1234-1236.

3.1 Quadrature Multiplexed BOC

- Receiving Techniques
  - Narrowband receiving: For low-complexity receivers, QMBOC can be treated as BOC(1,1)
    - Interoperability with GPS and Galileo
  - Wideband Receiving: For wideband receivers, QMBOC can be received and processed with full-band.
    - Better performance in anti-multipath
    - Similar baseband process with GPS L1C and Galileo E1 OS

[1] Zheng Yao, Mingquan Lu, and Zhenming Feng, Quadrature multiplexed BOC modulation for interoperable GNSS signals, *Electronics Letters*, 2010, 46(17): 1234-1236.

3.1 Quadrature Multiplexed BOC

- Acquisition and Tracking Performance
  - Power spectral density of QMBOC and TMBOC are the same.
  - When matched receiving, the acquisition and tracking performance are also same.
  - But for low-complexity receivers for BOC(1,1), QMBOC enables better performance
    - When only BOC(1,1) is processed, QMBOC has a 0.5 dB acquisition sensitivity gain than TMBOC
    - For 4 MHz receiving band, the tracking accuracy gain for QMBOC is 0.6164 dB
    - For 14 MHz receiving band, the tracking accuracy gain for QMBOC is 1.754 dB

[1] Zheng Yao, Mingquan Lu, and Zhenming Feng, Quadrature multiplexed BOC modulation for interoperable GNSS signals, *Electronics Letters*, 2010, 46(17): 1234-1236.

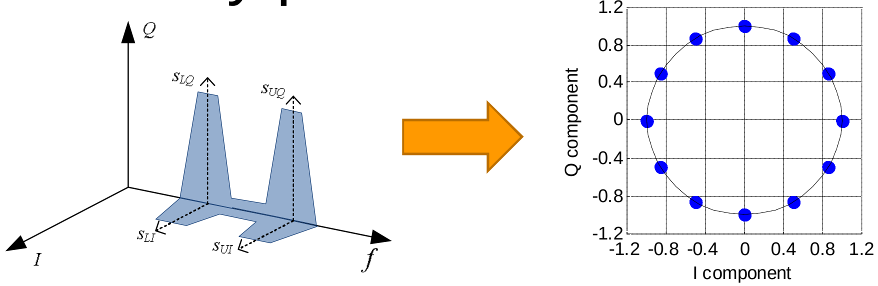
3.1 Quadrature Multiplexed BOC

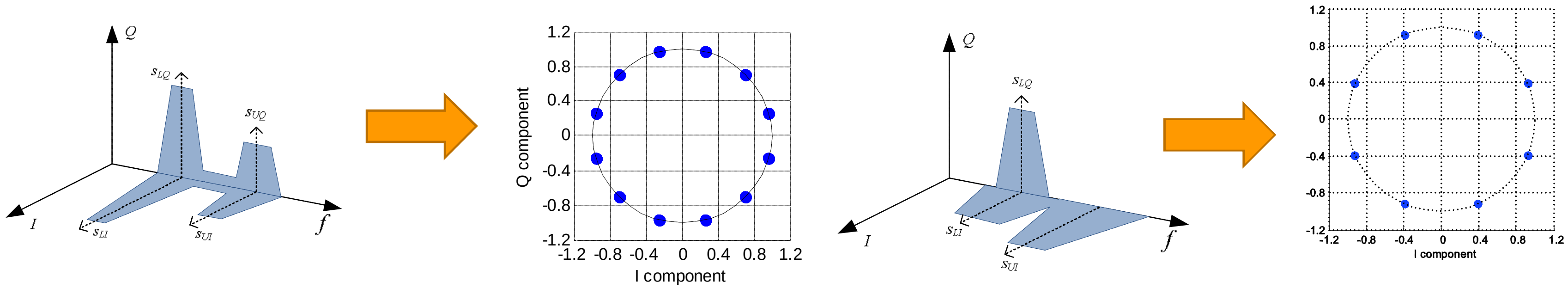
- Flexibility in Broadcast and Receiving
  - Keeping or cancelling the BOC(6,1) component of MBOC is always under debate in industry.
    - In QMBOC, BOC(6,1) is orthogonal to BOC(1,1), so BOC(6,1) can be seen as an enhancing component to BOC(1,1). For low-end and middle-end receivers, BOC(6,1) can be ignored. For high-end receivers BOC(6,1) can be received and improve the multipath performance.
    - Besides, the partition of BOC(6,1) among QMBOC is adjustable, future change of BOC(6,1) will not influence the existing receivers.
    - In contrast, TMBOC puts BOC(6,1) in fixed time slots. The partition of BOC(6,1) can hardly been adjusted or canceled.

[1] Zheng Yao, Mingquan Lu, and Zhenming Feng, Quadrature multiplexed BOC modulation for interoperable GNSS signals, *Electronics Letters*, 2010, 46(17): 1234-1236.

3.2 Asymmetric Constant Envelope BOC

- ACE-BOC -- Asymmetric Constant Envelope BOC
- ACE-BOC is a general multiplexing/ modulation technique, which allows the combination of no more than 4 signal components with any power allocation.



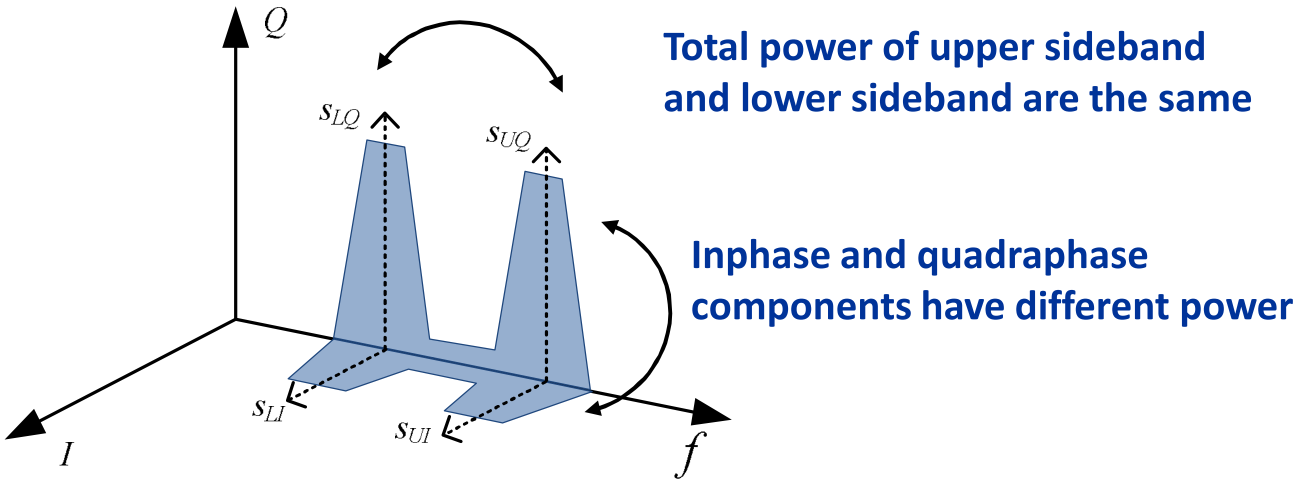


[1] Zheng Yao, Jiayi Zhang, and Mingquan Lu, ACE-BOC: Dual-frequency constant envelope multiplexing for satellite navigation, submitted to *IEEE Trans. on Aerospaces & Electronic Systems*, 2014

[2] Zheng Yao, and Mingquan Lu, Dual-frequency constant envelope multiplex with non-equal power allocation for GNSS, *Electronics Letters*, 2012, 48(25): 1624-1625.

3.2 Asymmetric Constant Envelope BOC

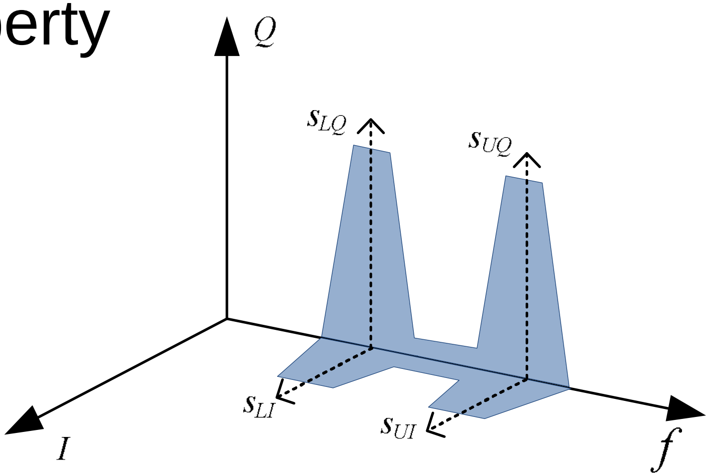
- The scheme for BeiDou B2[1] is a specific implementation of ACE-BOC.
  - B2a and B2b have equaled power
  - On each sideband, data : pilot = 1 : 3, modulation phase is orthogonal
  - PRN rate is 10.23 Mcps, subcarrier rate is 15.345 MHz



[1] Zheng Yao, and Mingquan Lu. ACED multiplexing and its application on BeiDou B2 band. Springer Lecture Notes in Electrical Engineering 244, 2013: 25-34.

3.2 Asymmetric Constant Envelope BOC

- Main Advantages of ACE-BOC
  - More power in pilot, acquisition and tracking performance is improved by 1.8 dB
  - Avoid drawbacks of Time Division
  - Interoperability with GPS L5 and Galileo E5
  - Intellectual property

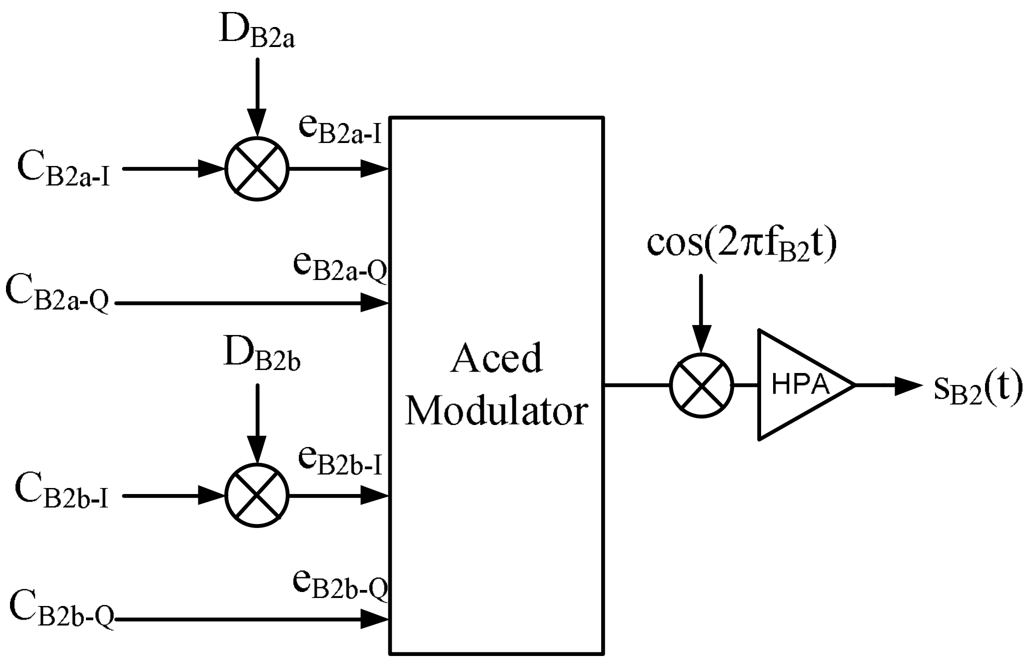


[1] Zheng Yao, Jiayi Zhang, and Mingquan Lu, ACE-BOC: Dual-frequency constant envelope multiplexing for satellite navigation, submitted to *IEEE Trans. on Aerospaces & Electronic Systems*, 2014

[2] Zheng Yao, and Mingquan Lu, Dual-frequency constant envelope multiplex with non-equal power allocation for GNSS, *Electronics Letters*, 2012, 48(25): 1624-1625.

3.2 Asymmetric Constant Envelope BOC

Generation of ACE-BOC Signal



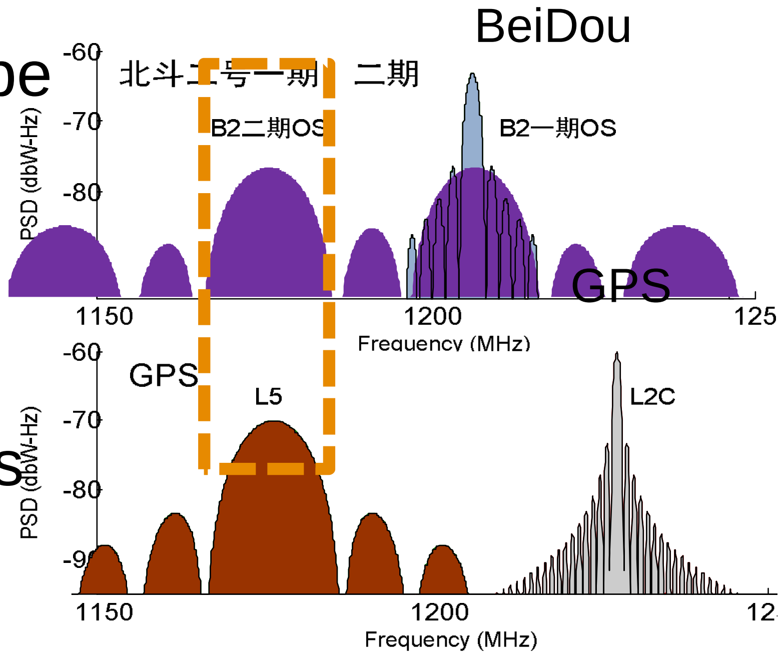
- Phase LUT technique to generate ACE-BOC signals
- Similar to AltBOC generation

3.2 Asymmetric Constant Envelope BOC

- Receiving of ACE-BOC signals
  - Similar to AltBOC
  - Narrowband receiving (Separate)
  - Wideband receiving

3.2 Asymmetric Constant Envelope BOC

- In ACE-BOC B2 Scheme, B2a can be treated as a QPSK(10) signal
- Share common receiving channel structure with L5
- Pilot power of ACE-BOC is 1.5 times



of AltBOC, which means:

(1) The tracking error variance under thermal noise of ACE-BOC is only 2/3 of AltBOC

(2) Tracking threshold under thermal noise is reduced by 1.8 dB compared with AltBOC

Outline

1 Background and Motivation

2 Constraints and Challenges

3 New Signal Structures for BeiDou

4 Some Test Results

5 Summary

4 Some Test Results

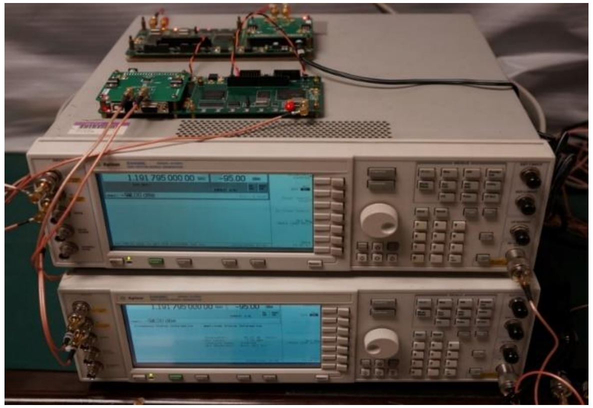
- Performance Analysis and Evaluation
  - Main items
    - acquisition sensitivity
    - tracking sensitivity
    - ranging accuracy
    - demodulation performance
    - Interference resistance (multiple access interference, near - far effect, etc.）
    - Interoperability
    - é é .

4 Some Test Results

- Performance Analysis and Evaluation (continued)
  - Main methods
    - theoretical analysis
    - computer simulation
    - semi-physical simulation and testing
    - é é

4 Some Test Results

- GNSS signal simulation and evaluation system



Signal Generator
（Baseband Unit +VSG）

GNSS Soft Receiver

4 Some Test Results

- A Case Study
  - Tracking Performance： ACE-BOC vs AltBOC

Power Ratio

AltBOC：Pilot/Data = 1:1

ACE-BOC：Pilot/Data = 3:1

Under the same total transmiting power, ACE-BOC has a higher pilot C/N0, but relative lower Data C/N0

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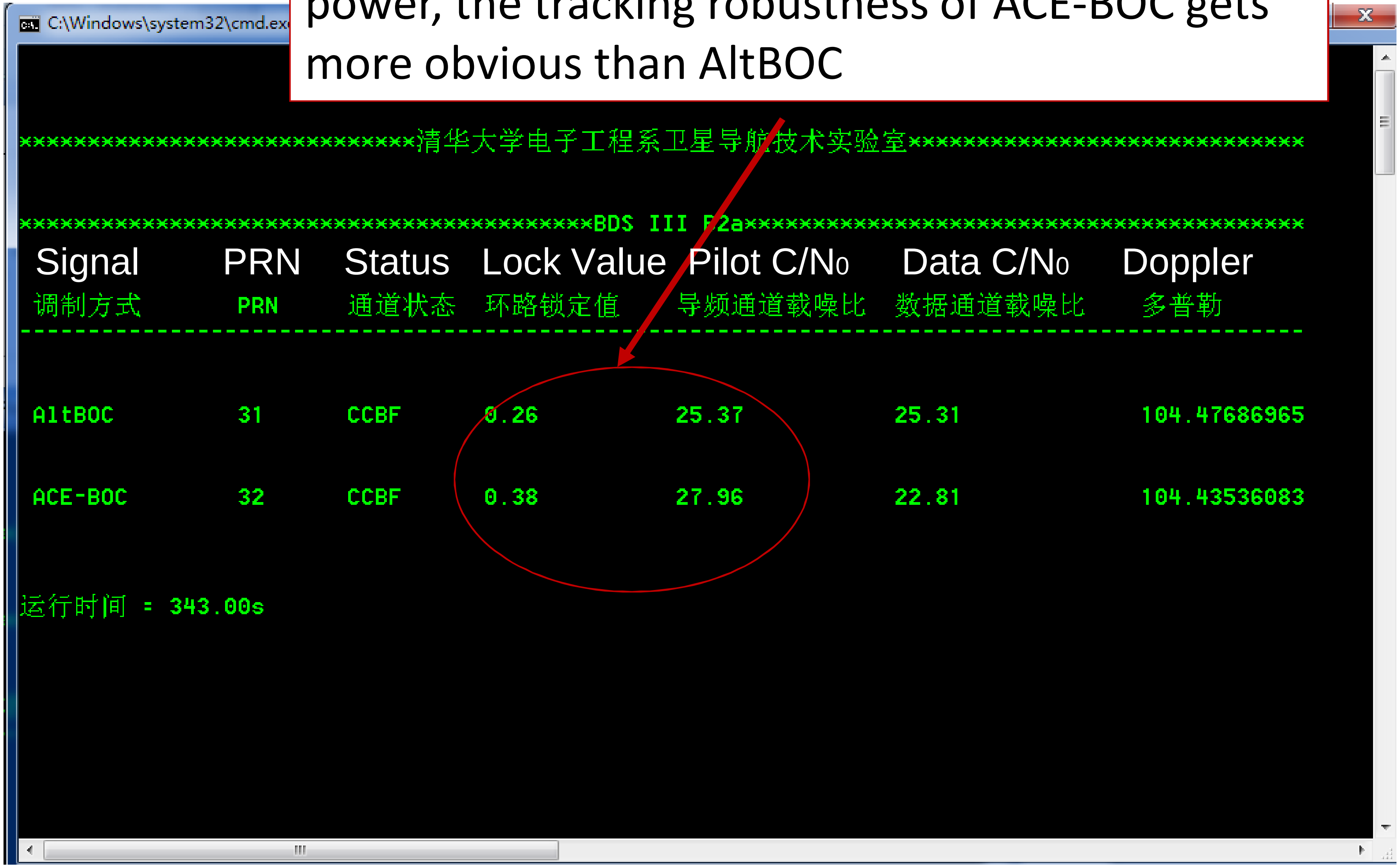
BDS III B2a

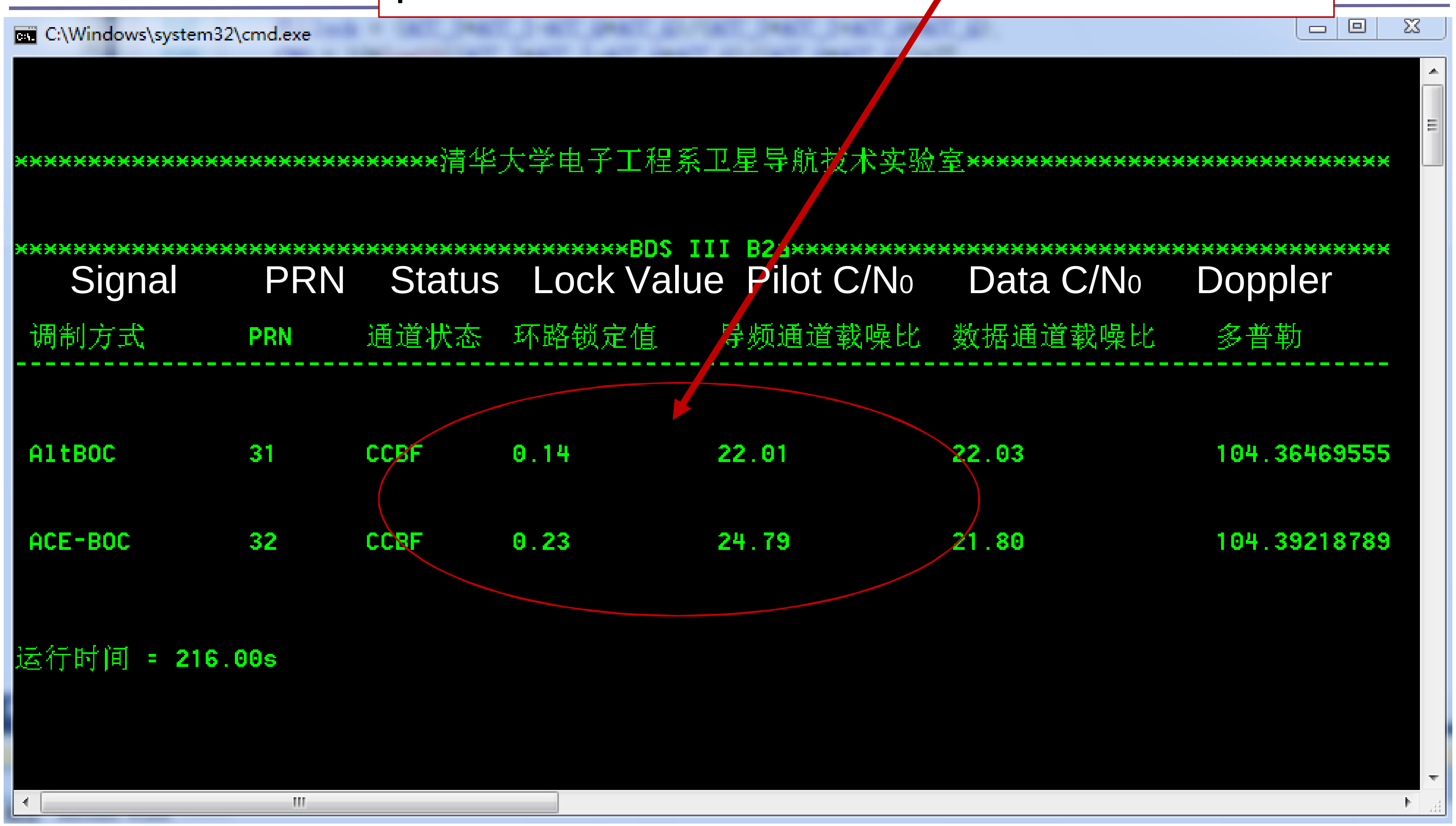
Signal 调制方式	PRN PRN	Status 通道状态	Lock Value 环路锁定值	Pilot C/N0 导频通道载噪比	Data C/N0 数据通道载噪比	Doppler 多普勒
AltBOC	31	CCBF	0.73	34.22	34.44	104.46226155
ACE-BOC	32	CCBF	0.82	36.59	31.36	104.43930937

运行时间 = 74.00s

ACE-BOC has a higher loop locked Value of pilot, more robust tracking while gradually reducing the both transmit signal power, the tracking robustness of ACE-BOC gets more obvious than AltBOC



To further reduce the both transmit signal power of AltBOC and ACE-BOC



In the same transmit power conditions, AltBOC loop has lost lock, while ACE-BOC remained stable tracking

Outline

5 Summary

- According to the current requirements, two novel signal structures, QMBOC and ACE-BOC, are proposed for China's BeiDou global navigation system.
- QMBOC is new signal structure with better performance and very flexible receiving techniques.
- ACE-BOC is a general modulation/ multiplexing technique, which allows the combination of no more than 4 signal components with any power allocation. The scheme for BeiDou B2 is a specific implementation of ACE-BOC, with very significant performance improvement.
- Both two signal structures are being further optimization and testing.
- The opinions and conclusions expressed in this presentation are those of the authors and should not be construed as representing the opinions or policy of any agency of the funding organizations.

New Signal Structures for BeiDou

B1C

	component	frequecy (MHz)	Modulation	Power Ratio	Phase
B1C	B1C_data	1575.42	BOC(1,1)	25%	0
	B1C_pilot	1575.42	QMBOC(6,1,4/33)	75%	0

B2

	Component	Frequency （MHz）	Modulation	Power Ratio	Phase
B2	B2a_data	1176.45	ACE-BOC(15,10)	12.5%	0
	B2a_pilot	1176.45		37.5%	90
	B2b_data	1207.14		12.5%	0
	B2b_pilot	1207.14		37.5%	90

Thanks for your attention!