International Technical Symposium
on Navigation and Timing

ENAC, 17 Nov 2015

BeiDou Next Generation Signal Design and Expected Performance

Challenges and Proposed Solutions

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- The views and opinions expressed in this presentation are those of the author and do not necessarily reflect the official policy or position of any agency of the funding organizations.

Outline

1 Background and Motivation

2 Constraints and Challenges

3 New Signal Structures for BeiDou

4 Some Test Results

5 Summary

1 Background and Motivation

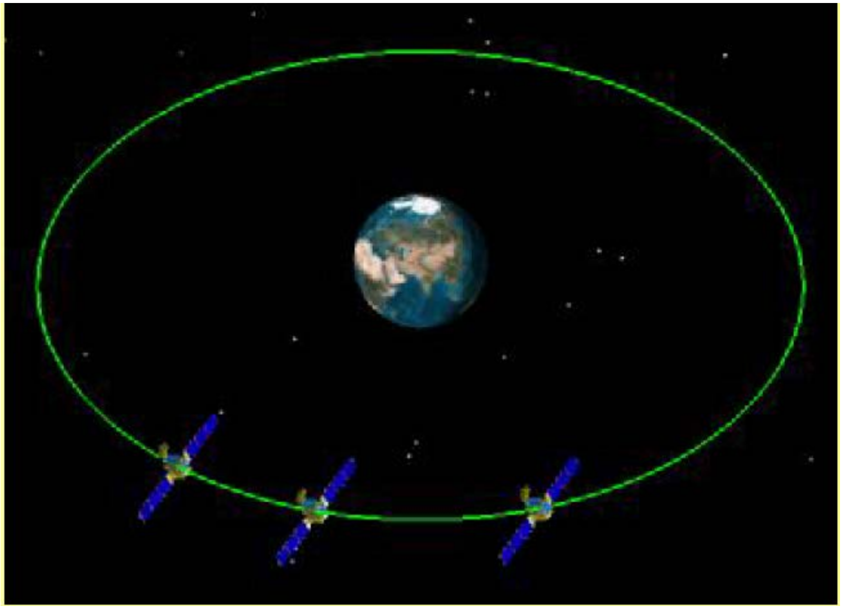
Development of GNSS Worldwide

- 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

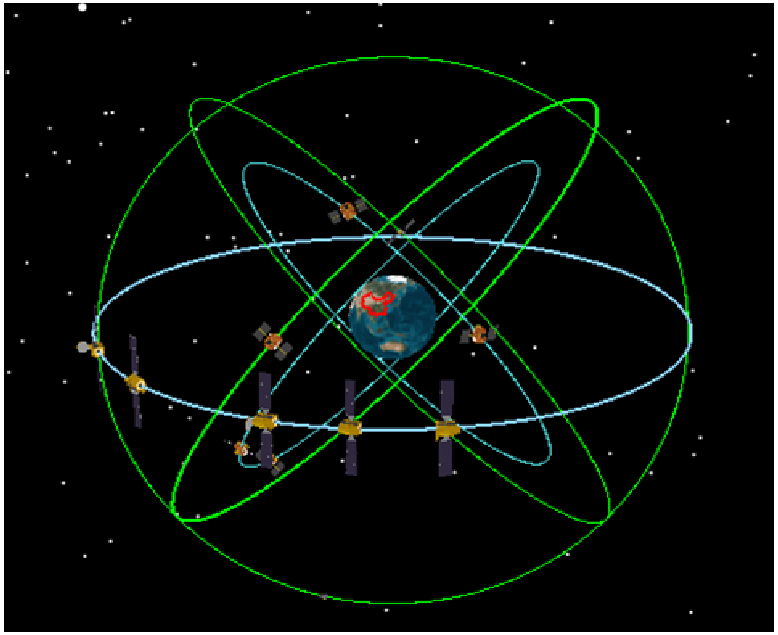
- **Three-step Plan**
- **First Step**: BeiDou Phase I, 2000~2012
  - Experimental system
  - SVs: 3 GEO satellites
  - Signals: L+S Band
  - Coverage: regional (China and its surrounding areas)
  - Status: closed



1 Background and Motivation

BeiDou Navigation Satellite System (cont.)

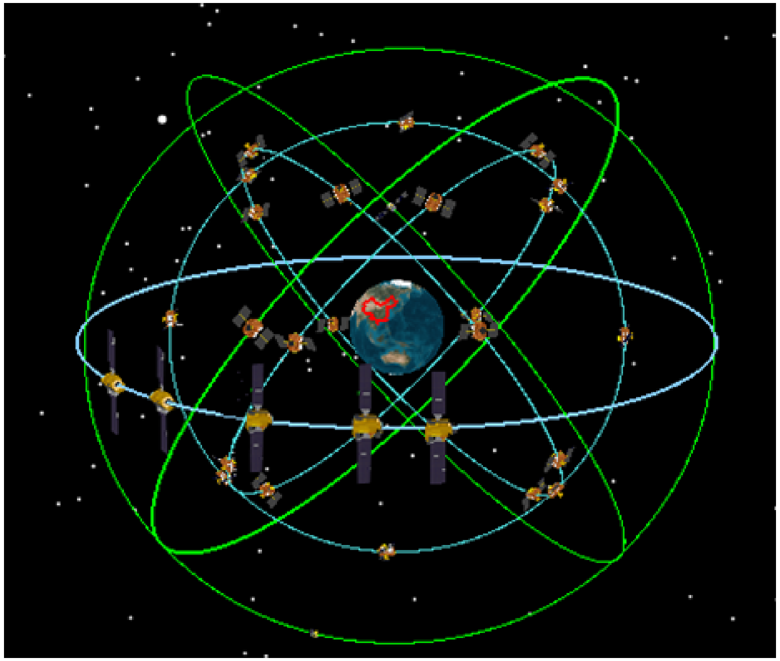
- **Second Step**: BeiDou Phase II, by 2012
  - Regional System
  - SVs: 14 satellites in orbit (5GEO+5IGSO+4MEO)
  - Signal: B1, B2, B3 (L Band)
  - Coverage: China and its surrounding areas
  - Status: FOC



1 Background and Motivation

BeiDou Navigation Satellite System (cont.)

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



1 Background and Motivation

- **Existing BeiDou Phase II (regional) Signals**
  - Two services: authorized service and open service
  - Two open service signals： B1(I), B2(I)
    - BPSK(2), 2.046Mcps
    - OS and AS signals (B1Q & B2Q) are in quadrature
    - 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	**OS**
B1(Q)		2.046			AS
B2(I)	**1207.14**	2.046	24	QPSK	**OS**
B2(Q)		10.23			AS
B3	1268.52	10.23	24	QPSK	AS

1 Background and Motivation

Signal Design for BeiDou Phase III (global)

- 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.

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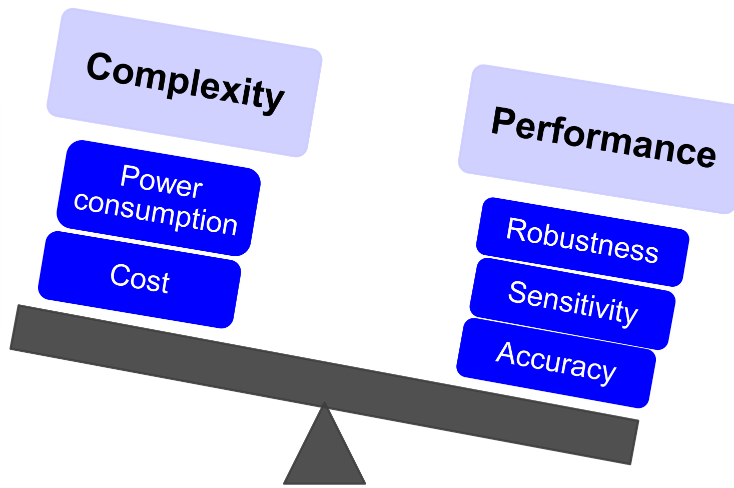
Top-level Design of Signal Architecture

- **New Signals of BeiDou Phase III in the Plan**
  - Two different services will 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)

Where and How GNSS Signals Will be Used?

- **GNSS is a large infrastructure system**
  - Long construction cycle
  - Long expected service life

- **Impossible to accurately predict the future**



- **The requirement from different applications may be conflicting**

Typical Receiver Modes

- **High-end Mode (HM)**
  - Accuracy is most important while realization complexity is secondary
  - Computationally intensive algorithms are acceptable as long as accuracy benefit can be obtained
- **Low-end Mode (LM)**
  - Sensitive to complexity (cost and power consumption) and sensitivity
  - Accuracy is not critical
- **Mid-end Mode (MM)**
  - Cost and power consumption are important but restrictions are not as rigorous as in low-end mode
  - Balance between performance and complexity

Requirements of Different Modes

- **LM Rx**
  - Single frequency processing
  - Higher carrier frequency, lower ionospheric correction error
  - Narrow band receiving with relatively simple processing strategy
- **HM Rx & a part of MM Rx**
  - Dual-frequency processing estimates ionospheric group delay
  - Multipath and thermal noise become the major error sources
  - Signals with wider RMS bandwidths are desired
- For some single frequency receivers which can obtain differential correction information, wider RMS bandwidth is also desired

Feature Requirements of B1C

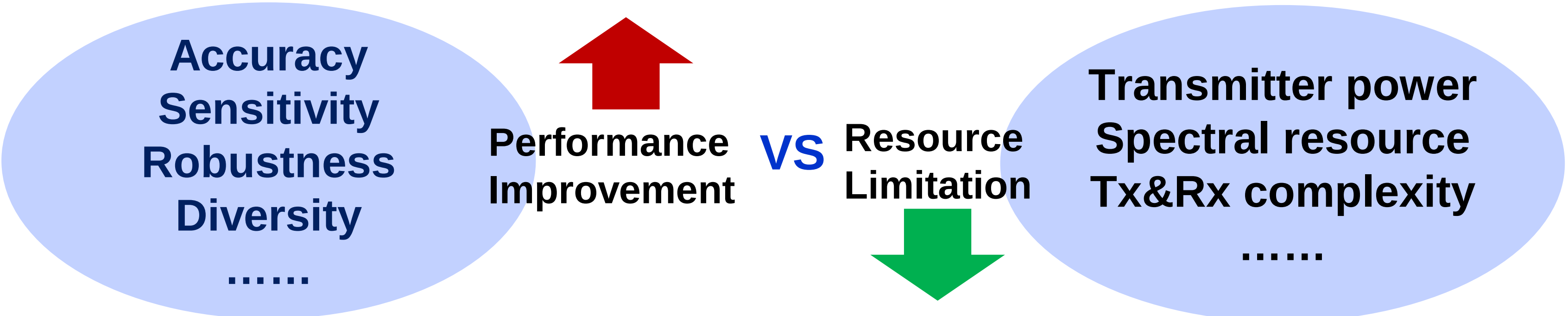
	Feature Requirements	Representative Users
B1C	Has multiple possible processing strategies for diversified applications	LM: Consumer electronics, Sensors in IoT, ect. HM/MM: Primary signal in dual-frequency Rx. Geodesy, precise engineering surveying, and precision agriculture etc.
	Wide RMS bandwidth to improve inherent accuracy and anti-multipath ability	
	Narrowband low complexity processing strategy for low-end receivers	
	Compatibility and Interoperability with GPS and Galileo	

Feature Requirements of B2a/B2b

	Feature Requirements	Representative Users
B2	Works along with B1C, optimized for high precision ranging measuring	HM: Primary signal in dual-frequency Rx. Geodesy, precise engineering surveying, and precision agriculture etc.
	Wide RMS bandwidth to improve inherent accuracy and anti-multipath ability	
	Robust to enable tracking in challenging environments	
	Compatibility and Interoperability with GPS and Galileo	

Challenges in GNSS Signal Design

- **Main Challenges in GNSS Signal Design**
  - The primary contradiction between performance improvement vs. resource limitation



- **Limitation of spectrum and payload power**
  - Unrealistic to broadcast multiple signals each specialized for a specific types of application

- **One challenge is designing flexible signals**
  - Allow using different processing strategies to meet the requirements of both LM and HM applications

Challenges in GNSS Signal Design

Additional Challenges

- Coexistence of legacy and new signals / Smooth transition from Phase II to Phase III
- Compatibility and interoperability between multiple GNSSs
- ……

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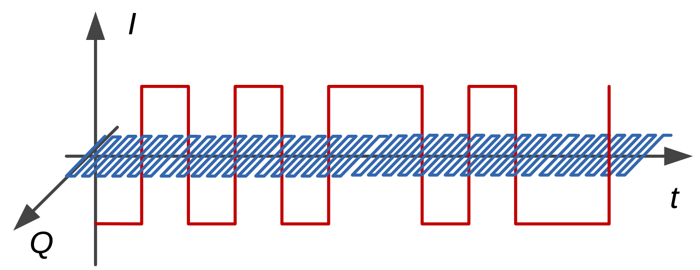
3.1 Quadrature Multiplexed BOC

- **B1C signal should meet varied requirements simultaneously**
  - Inherent high ranging accuracy
  - Low-complexity processing strategies
  - Good interoperability with GPS L1C and Galileo E1 OS

- **Quadrature Multiplexed BOC (QMBOC)** [1]
  - BOC(1,1) and BOC(6,1) are modulated on two quadrature phases, with same PRN code or different PRN codes

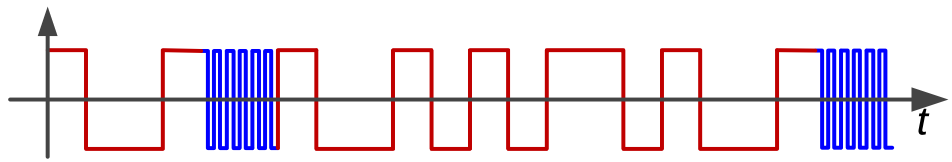


$$\begin{aligned} s_d(t) &= c_d(t)\,d(t)\,s_{\mathrm{QMBOC}}(t) \\ &= \sqrt{1-\gamma}\,c_d(t)\,d(t)\,s_{\mathrm{BOC}(n,n)}(t) \pm j\sqrt{\gamma}\,c_d(t)\,d(t)\,s_{\mathrm{BOC}(m,n)}(t) \end{aligned}$$

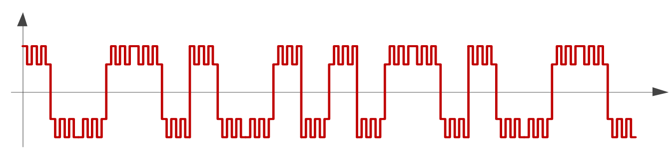
[1] Zheng Yao, Mingquan Lu, and Zhenming Feng, Quadrature multiplexed BOC modulation for interoperable GNSS signals, *Electronics Letters*, 2010, 46(17): 1234-1236.

Different MBOC Implementations

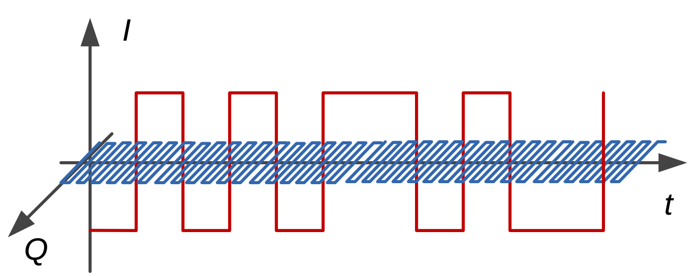
- **Time-multiplexed BOC (TMBOC)**
  - Combining BOC(1,1) and BOC(6,1) in <u>time multiplexing</u> way



- **Composite BOC (CBOC)**
  - <u>Weighted summation</u> of BOC(1,1) and BOC(6,1)



- **Quadrature multiplexed BOC (QMBOC)**
  - BOC(1,1) and BOC(6,1) are modulated in <u>phase quadrature</u> with each other

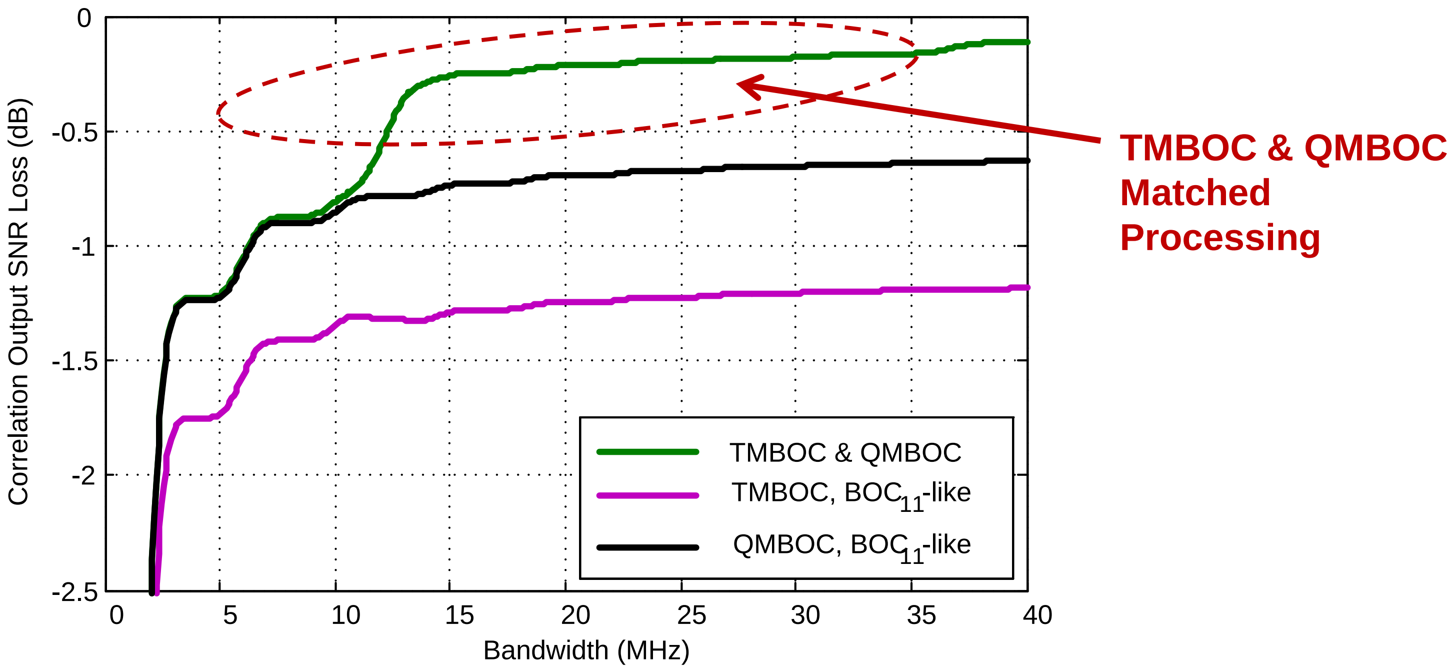


Typical Receiving Strategies

- **Narrowband receiving**
  - For low-complexity receivers, QMBOC can be treated as BOC(1,1)
  - Common channel can be used to process B1C, L1C and E1 OS signals
  - Interoperability with GPS and Galileo

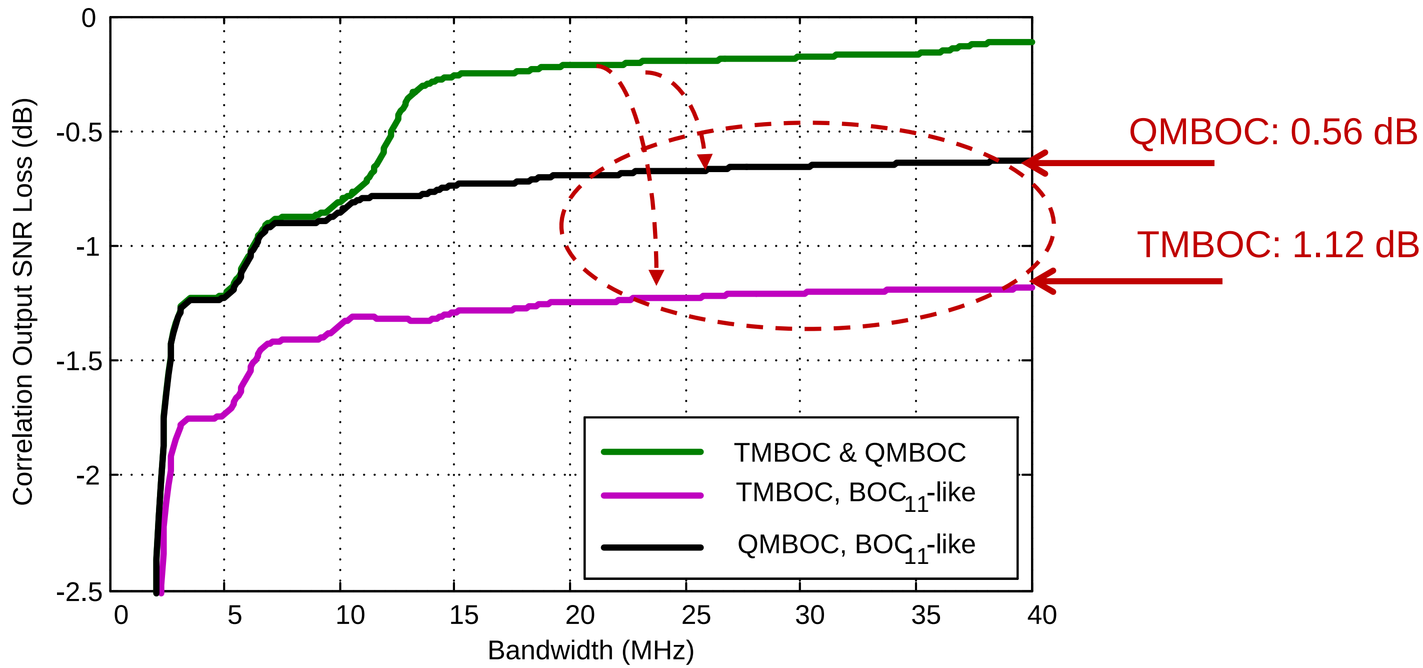
- **Wideband Receiving**
  - For wideband receivers, QMBOC can be received and processed with full-band.
  - Better performance in anti-multipath
  - Similar baseband process with GPS L1C and Galileo E1 OS

Acquisition Performance



- **QMBOC vs. TMBOC**
  - In matching receiver, QMBOC and TMBOC have the same performance

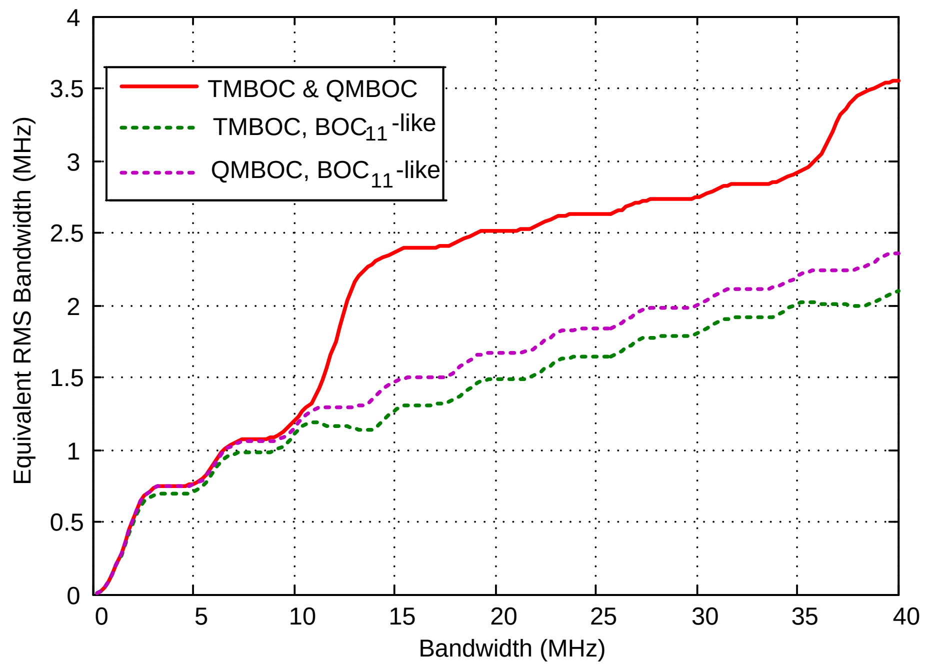
Acquisition Performance



- **QMBOC vs. TMBOC**
  - In BOC_{11}-like receivers, QMBOC has better performance
    - QMBOC: SNR loss -0.56 dB (=29/33)
    - TMBOC: SNR loss -1.12 dB (=(29/33)^2)
      - in BOC(6,1) slot, there is no signal, but noise can enter correlator

Tracking Performance

- **Equivalent RMS bandwidth**
  - Local de-spreading signal waveform dependent

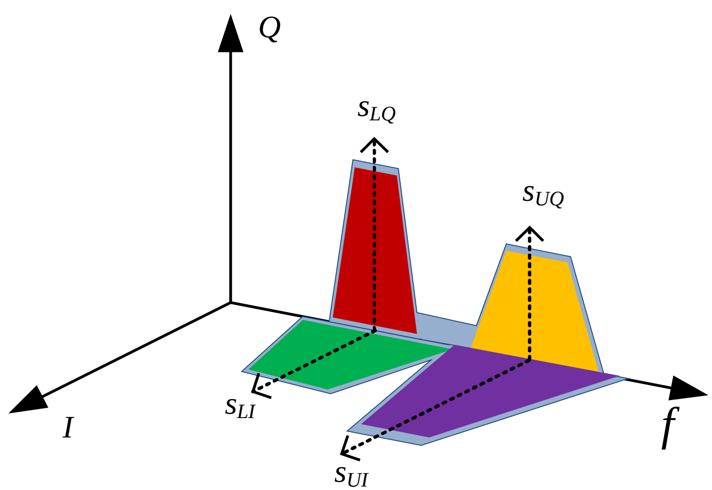


- **QMBOC vs. TMBOC**
  - With MBOC local replica and a wide front-end bandwidth, both QMBOC and TMBOC can have a high tracking accuracy
  - In BOC_{11}-like receivers, with wide bandwidth, QMBOC is superior to TMBOC

3.2 Asymmetric Constant Envelope BOC

Asymmetric Constant Envelope BOC (ACE-BOC)

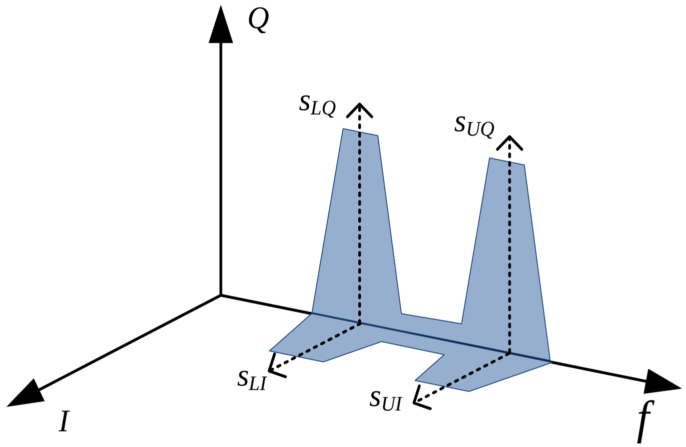
- A general deal-frequency multiplexing/ modulation technique
- Combine 4 or fewer codes with arbitrary power splitting into a spectrum-split constant envelope signal
- Higher proportion of the transmission power can be allocated to pilot channels or primary service components
- Any component can be halted without influencing the constant envelope property



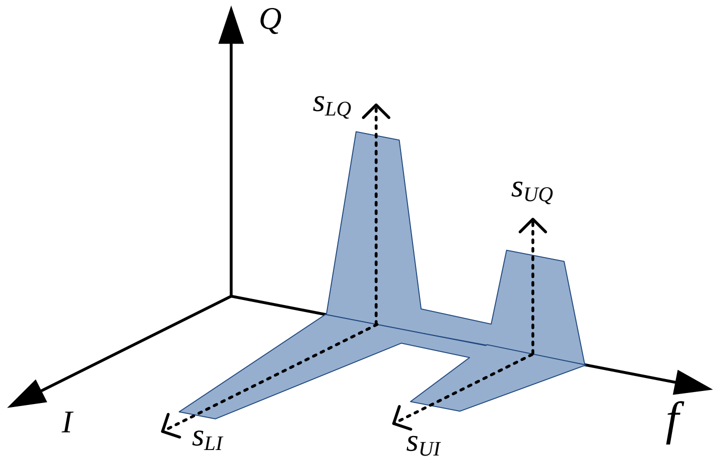
[1] Zheng Yao, Jiayi Zhang, and Mingquan Lu, ACE-BOC: Dual-frequency constant envelope multiplexing for satellite navigation, *IEEE Trans. on Aerospaces & Electronic Systems*, Volume 52, Issue 2, 2016

[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.

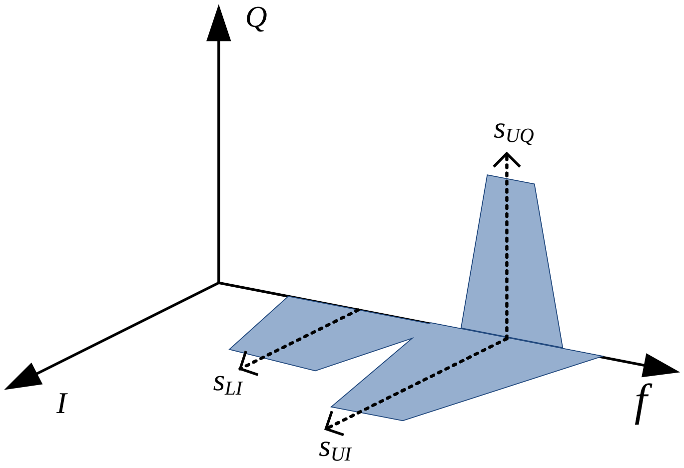
Typical Embodiments of ACE-BOC



Case 1: Allocating more power to pilot channels to improve the acquisition and tracking performance



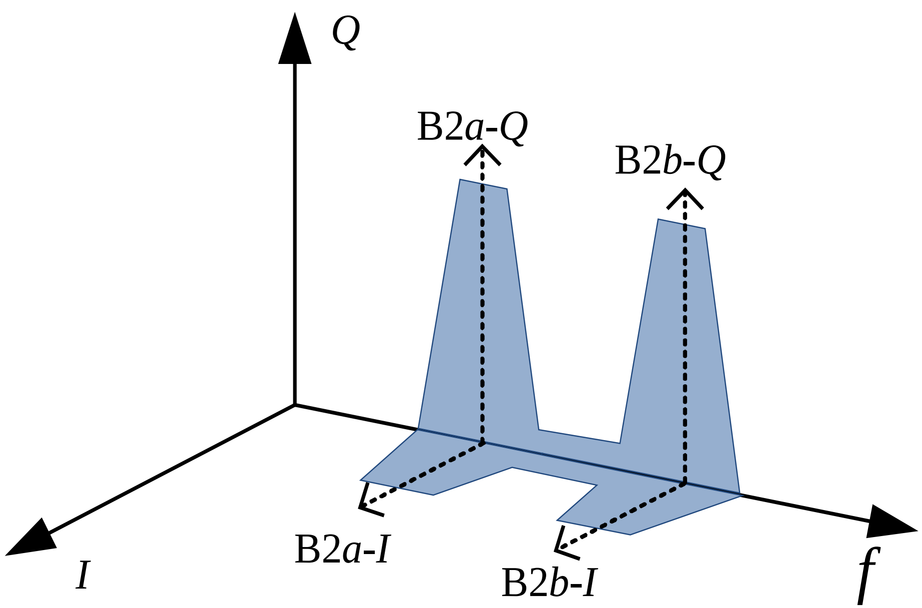
Case 2: augment the power of one sideband



Case 3: Deal with the smooth transition issue in system updating

3.2 Asymmetric Constant Envelope BOC

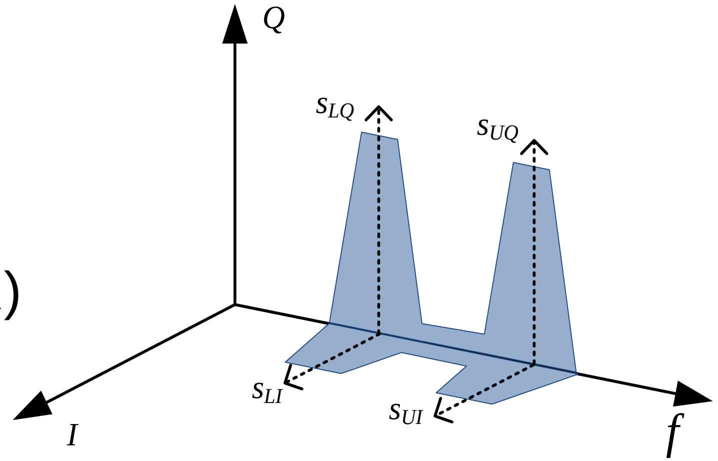
- **The scheme for BeiDou B2 is a specific implementation of ACE-BOC**.
  - PRN rate 10.23Mcps, subcarrier rate 15.345MHz
  - B2a and B2b have equaled power
  - On each sideband, data : pilot = 1 : 3, modulation phase is orthogonal



3.2 Asymmetric Constant Envelope BOC

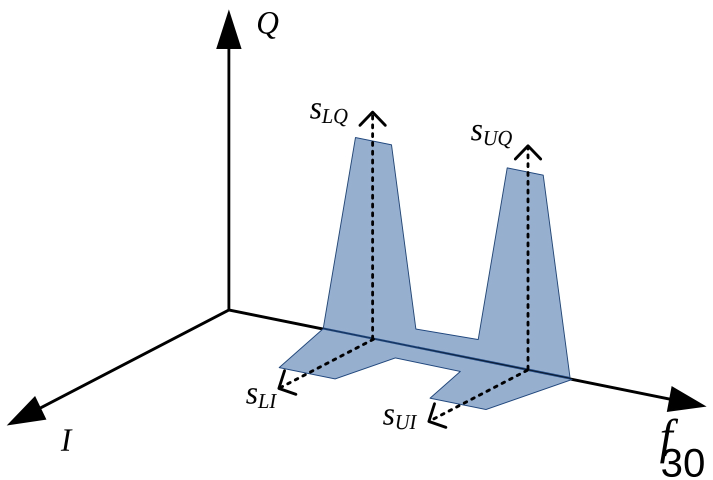
Main Advantages of ACE-BOC

- More power in pilot, acquisition and tracking performance is improved by 1.8dB
- Interoperability with GPS L5 and Galileo E5
  - All of these three signals can be treated as QPSK(10) and share the same channel structure
- <u>Flexible processing strategies</u>
  - Fullband matched receiving (FMR)
  - Independent matched receiving (IMR)
  - BPSK-like receiving (BLR)

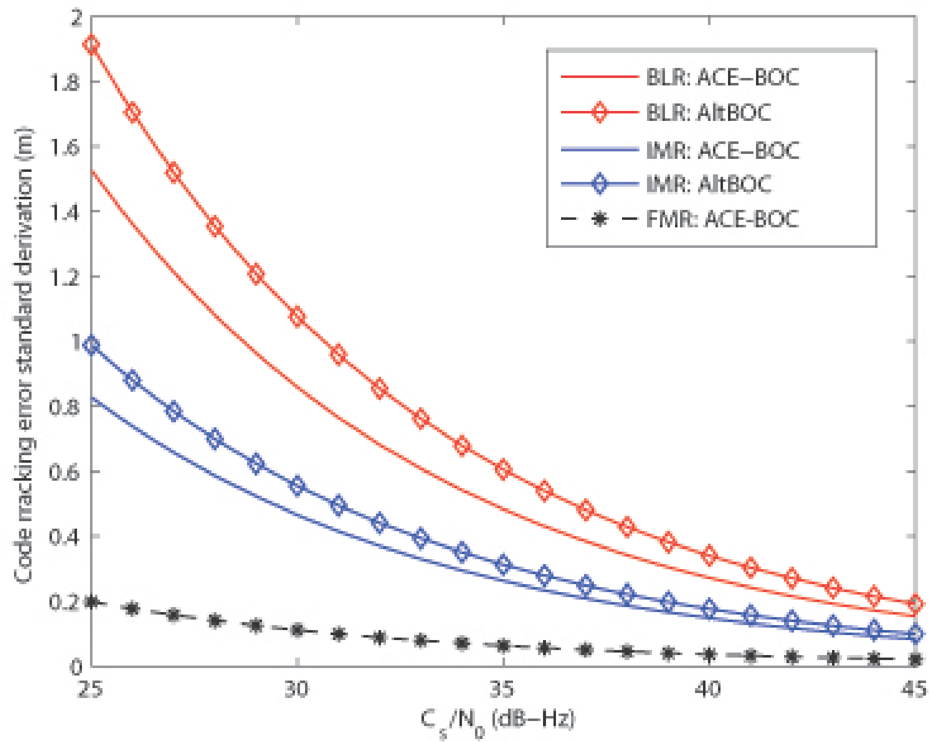


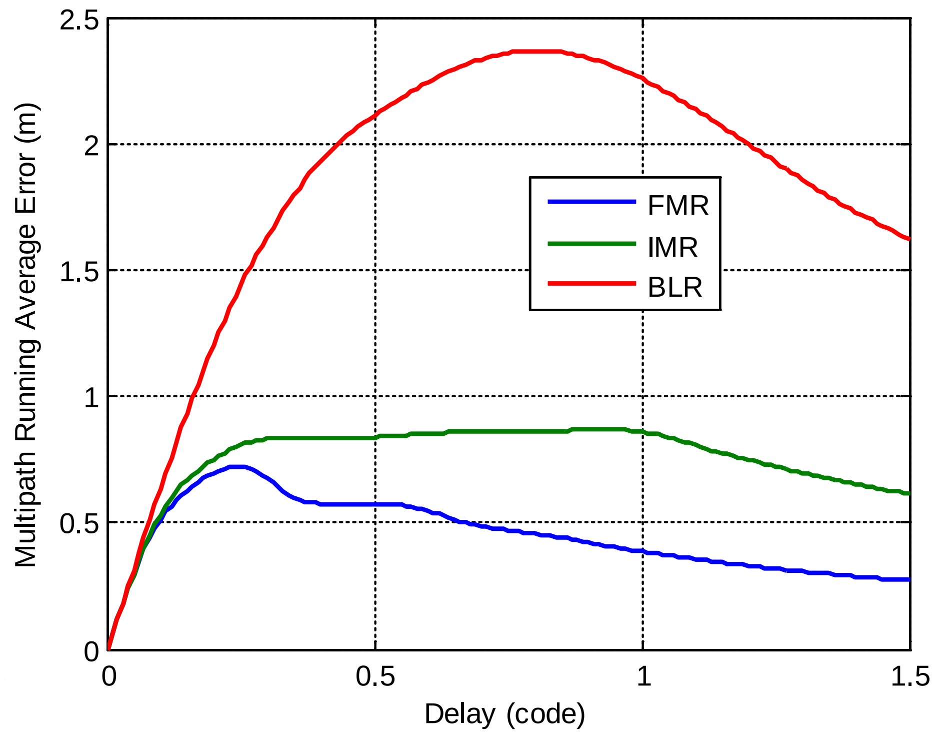
Flexible Processing Strategies

- **Fullband matched receiving (FMR)**
  - Entire ACEBOC signal can be as the local replica, make the best use of the signal power, but with the highest processing complexity
- **Independent matched receiving (IMR)**
  - Receive every signal component separately with local replica of multi-level subcarrier
- **BPSK-like receiving (BLR)**
  - Treated as two QPSK signals and received separately
  - Requires less front-end bandwidth and processing complexity
  - The most commonly accepted receiving mode



Flexible Processing Strategies





[1] Zheng Yao, Jiayi Zhang, and Mingquan Lu, ACE-BOC: Dual-frequency constant envelope multiplexing for satellite navigation, *IEEE Trans. on Aerospaces & Electronic Systems*, Volume 52, Issue 2, 2016

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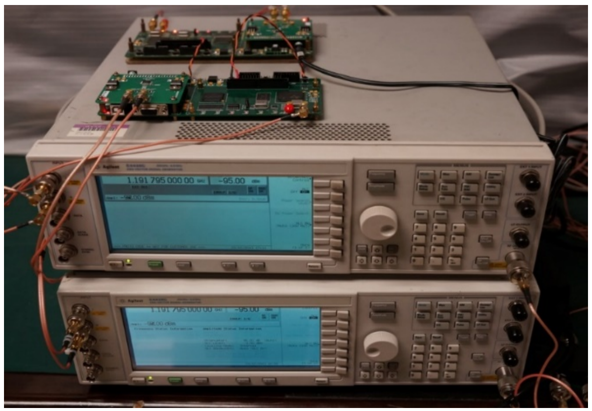
4 Some Test Results

- **Main items in performance analysis and evaluation**
  - Acquisition sensitivity
  - Tracking sensitivity
  - Ranging accuracy
  - Demodulation performance
  - Interference resistance
  - Compatibility
  - …….

- **A series of performance evaluation has been carried out for each signal structure option of BeiDou global system**
  - Theoretical analysis
  - Computer simulations in signal-level
  - Ground test with signal simulator and receivers prototype
  - Satellite-to-receiver validation

4 Some Test Results

- GNSS signal simulation and evaluation system



Signal Generator
（Baseband Unit +VSG）

GNSS Receiver

4 Some Test Results

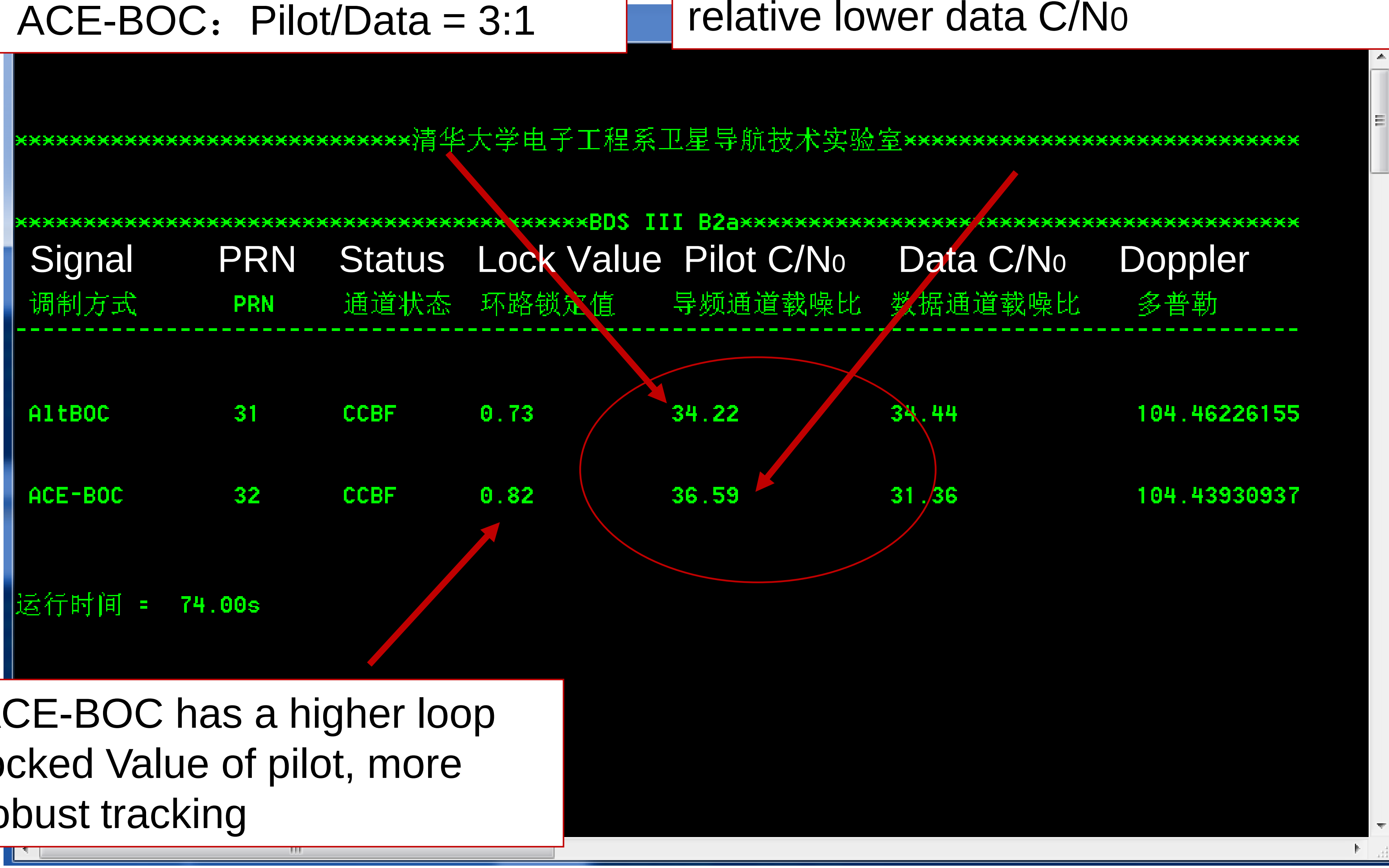
- **A Case Study**
  - Tracking Performance：ACE-BOC vs AltBOC
    - ACE-BOC and AltBOC with same total transmit power
    - BPSK-like receiving strategy, sharing channel
    - Acquisition and tracking channels for them are totally the same
    - Pilot component tracking, aiding data demodulation

Power Ratio

AltBOC：Pilot/Data = 1:1

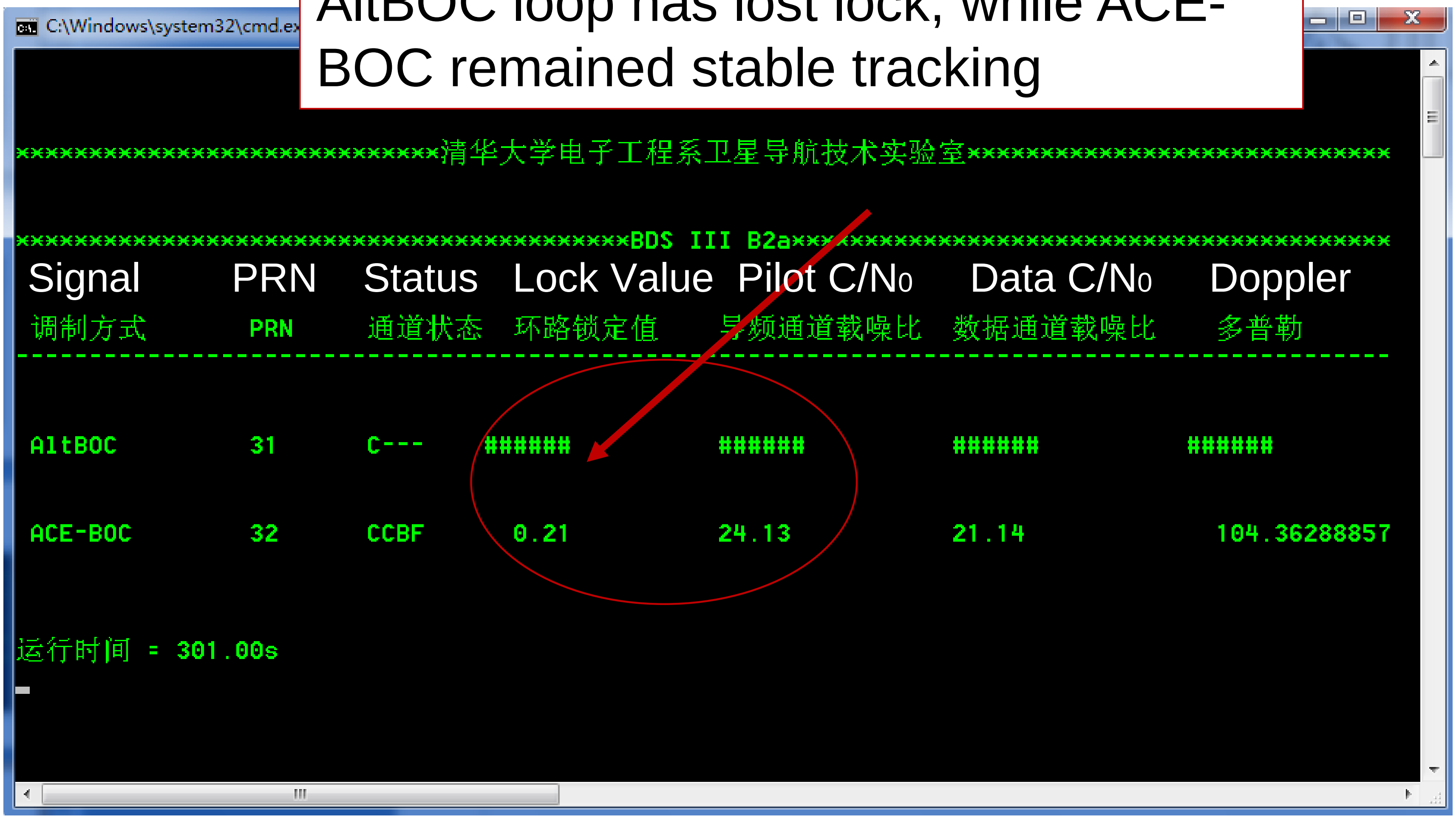
ACE-BOC：Pilot/Data = 3:1

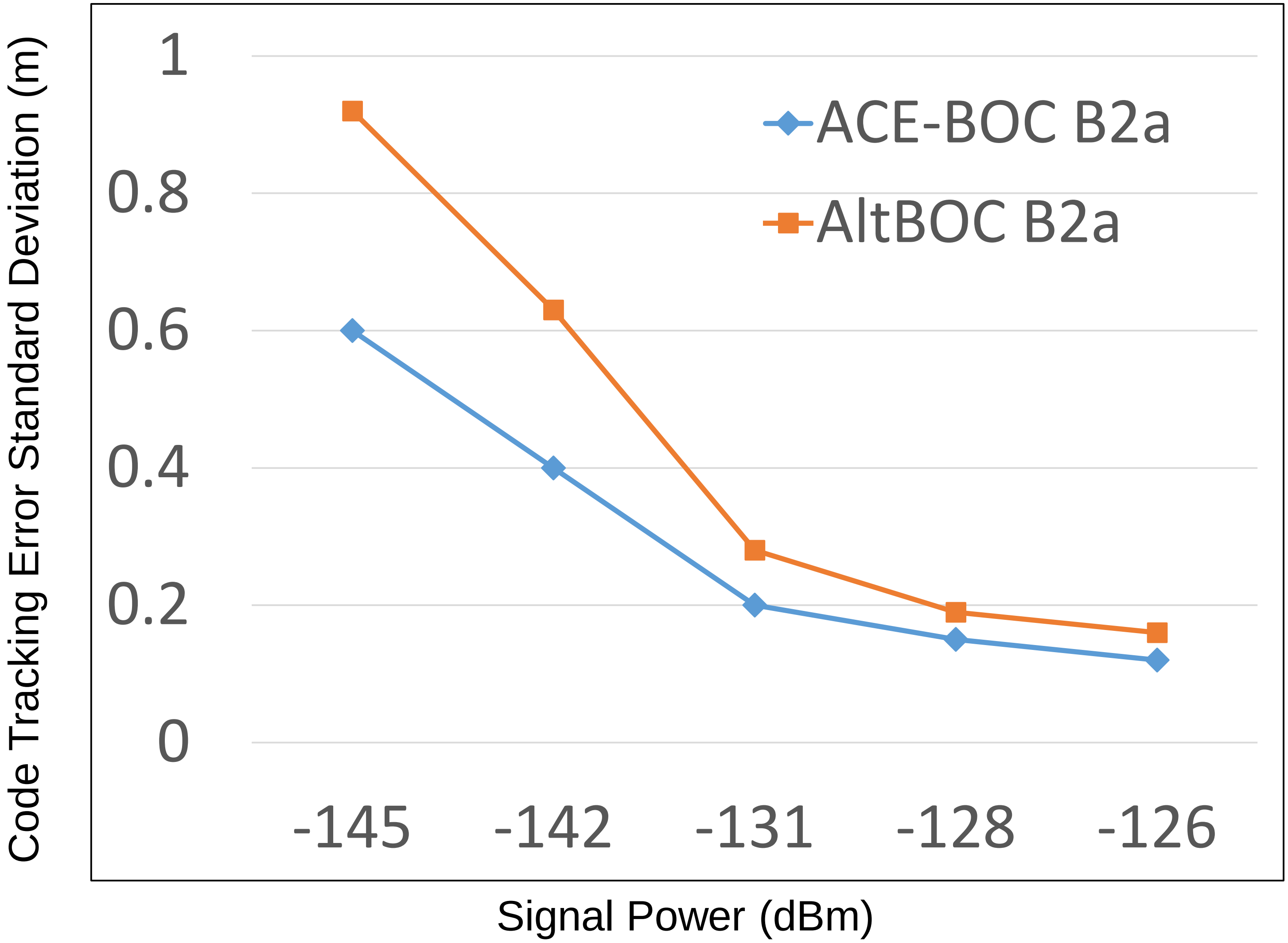
Under the same total transmit power, ACE-BOC has a higher pilot C/N0, but relative lower data C/N0



ACE-BOC has a higher loop locked Value of pilot, more robust tracking

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




Code Tracking Error Standard Deviation (m)
1
0.8
0.6
0.4
0.2
0
ACE-BOC B2a
AltBOC B2a
-145
-142
-131
-128
-126
Signal Power (dBm)

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- As new generation GNSS evolves, a number of new signal structures are emerging
- Although GNSS future cannot be predicted accurately, the inherent various receiving strategies can make signals construct multiple balance points between complexity and performance for both transmitters and receivers, thus provide more diversified choices for system designers as well as users
- According to the system construction requirements, two novel GNSS signal structures, QMBOC and ACE-BOC, are proposed for China's BeiDou global navigation system.

5 Summary

- QMBOC is new signal structure with better performance and flexible receiving techniques.
- ACE-BOC is a general modulation/ multiplexing technique, which allows the combination of 4 or fewer signal components with any power allocation.
- The scheme for BeiDou B2 is a specific implementation of ACE-BOC, with significant performance improvement, and diversified receiving strategies.
- Both of these two signal structures have good compatibility and interoperability with GPS and Galileo.

Thank you for your attention!