An Open Source BDS-3 B1C/B2a SDR Receiver

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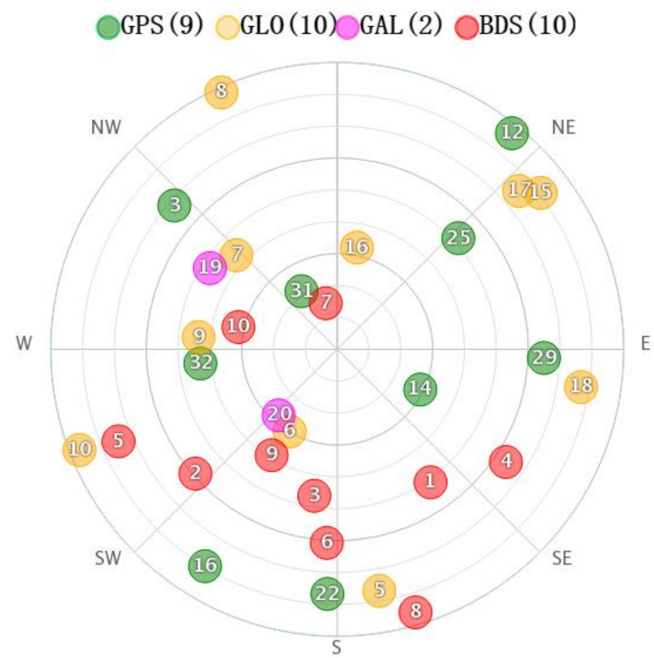
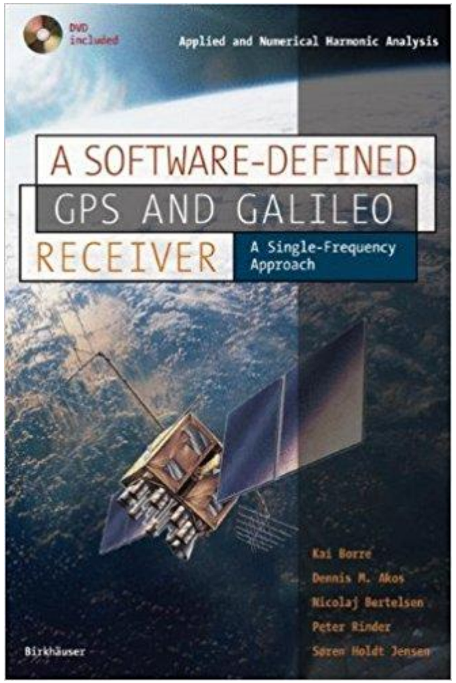
Open Source Archive of GNSS SDRs Development at CU, Boulder (1/2)

- **Added**
  - GPS L2C (data + pilot)
  - GPS L5C (data + pilot)
  - GLONASS L1 C/A
  - GLONASS L2 C/A
  - Galileo E1 (data + pilot)
  - Galileo E5a (data + pilot)
  - Galileo E5b (data + pilot)
  - BDS-2 B1
  - BDS-2 B2



- **Focus of this presentation/paper**
  - BDS-3 B2a (data + pilot)
  - *BDS-3 B1C (data + pilot)*



GPS L1 C/A only

Open Source Archive of GNSS SDRs Development at CU, Boulder (2/2)

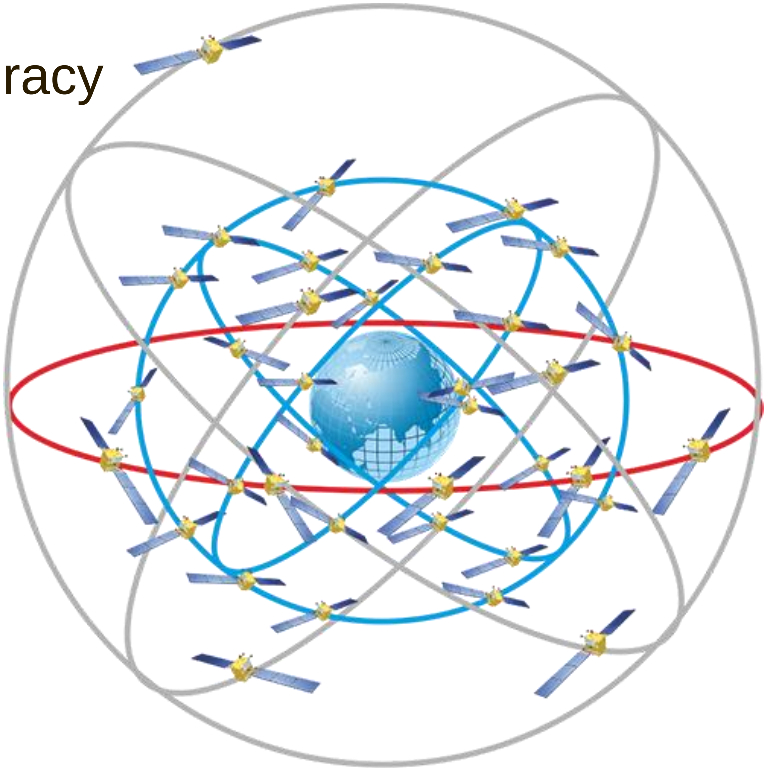
- **Features**
  - Post-processing
  - Supports variable # of IF bits and file formats (complex / real)
  - Supports ION GNSS Software Defined Receiver Metadata Standard
- **Implemented in MATLAB**
  - **Flexible tool for research**
  - Easy to realize and operate
  - Exploration of advanced signal processing algorithms with real IF data or simulated data
  - Slow, not suitable for real-time operation

☞ **Open source (soon available)**
  - **Github**
  - **http://ccar.colorado.edu/gnss/**

Status of Third Generation BDS (1/3)

➢ BDS phase Ⅲ (BDS-3) constellation

- 4 MEO SVs already in commissioning
- Yet to be deployed:
  - **3 GEO** + **3 IGSO** + **20 MEO** + reserved ones as needed
- Rubidium and hydrogen atomic clocks
- Inter-satellite links
- Improved Signal-In-Space (SIS) accuracy
- First version of ICD (Chinese) for the new signals was released on September 5, 2017
  - http://www.beidou.gov.cn/xt/gfxz/



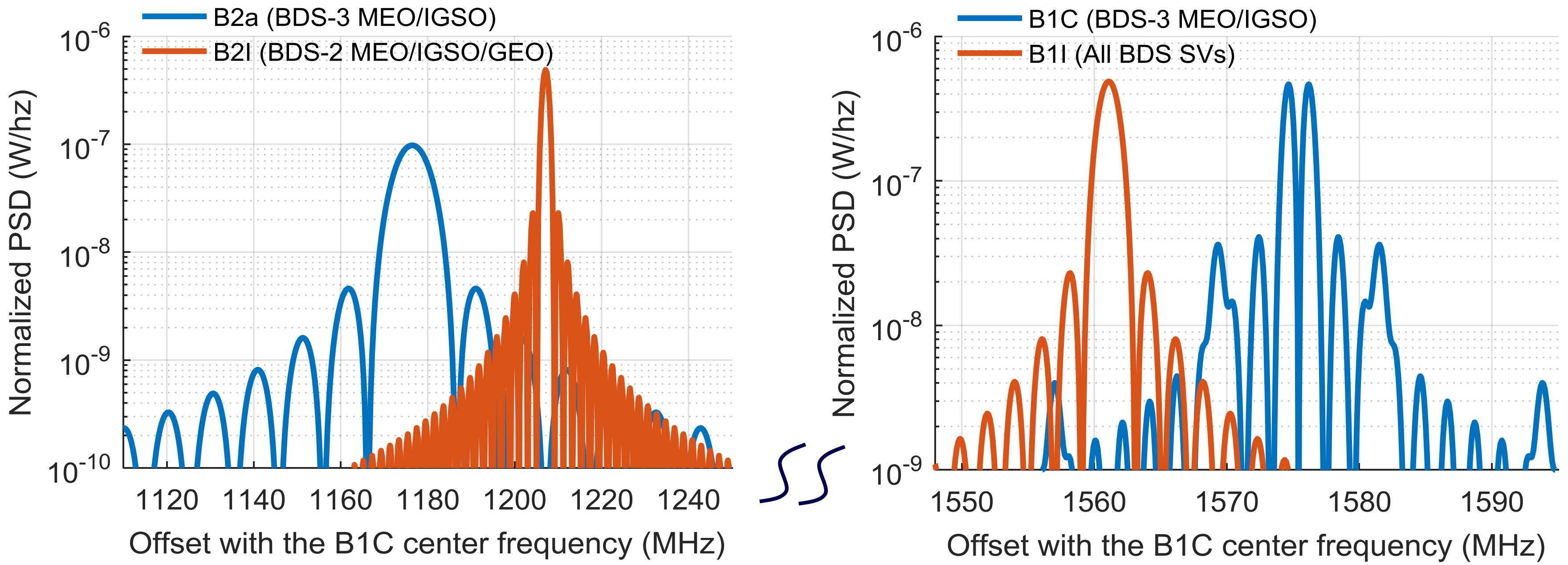
Status of Third Generation BDS (2/3)

- **BDS phase Ⅲ (BDS-3) constellation**

Satellites	Launch date	PRN	Orbit	Status
BeiDou-3 M1	2017-11-05	19	MEO	In commissioning
BeiDou-3 M2		20	MEO	In commissioning
BeiDou-3 M7	2018-01-11	27	MEO	In commissioning
BeiDou-3 M8		28	MEO	In commissioning
BeiDou-3 M5	2018-02-12	Unknown	MEO	Upcoming
BeiDou-3 M6		Unknown	MEO	Upcoming

Status of Third Generation BDS (3/3)

- BDS-3 open service signals with ICD released



B1C/B2a Signal Structure (1/4)

Structure of B1C and B2a signals

Signals	Component	Carrier freq. (MHz)	Bandwidth (MHz)	Modulation mode	Nav data rate (sps)	Service type
B1C	data	1575.42	32.736	BOC(1,1)	100	RNSS*
	pilot	1575.42		QMBOC(6,1,4/33)	0	RNSS
B2a	data	1176.45	20.46	QPSK(10)	200	RNSS
	pilot	1176.45			0	RNSS

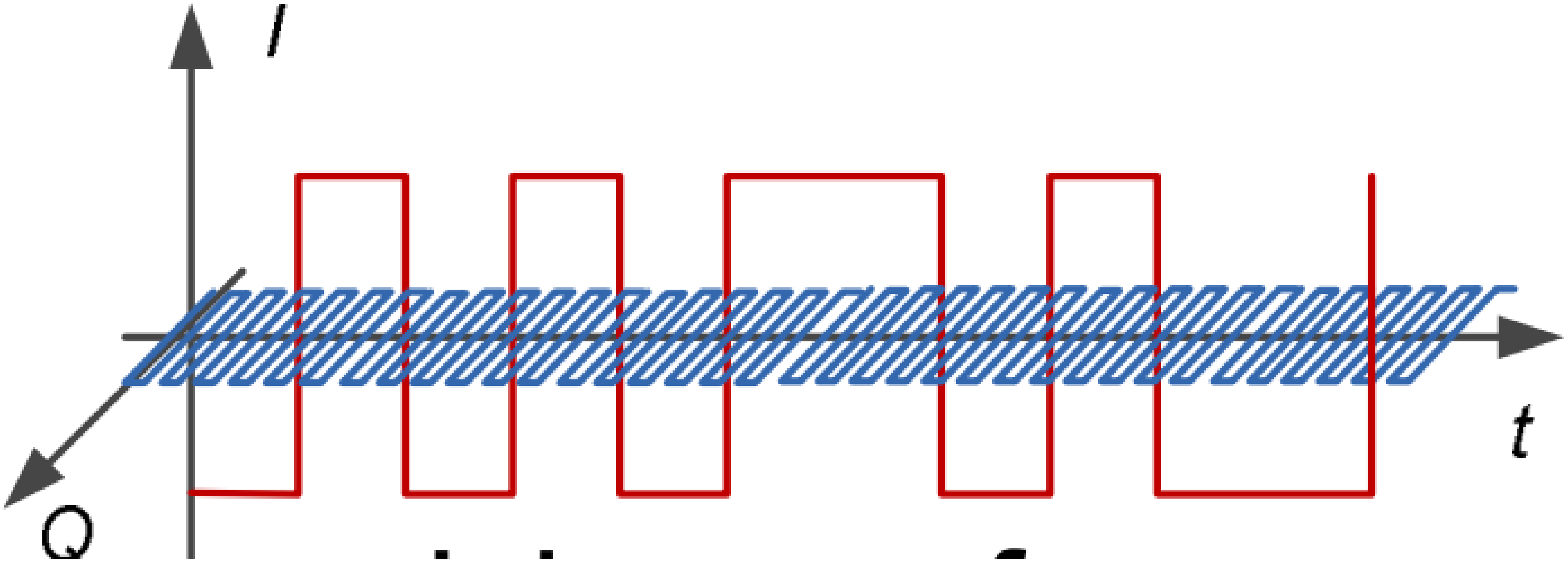
*RNSS: Radio Navigation Satellite Service

Key features

- Date channel & pilot channel
- Increased Nav data rate compared to B1I/B2I transmitted by MEO/IGSO
- QMBOC(6,1,4/33): the most complex modulation of the BDS open service signals to date

B1C/B2a Signal Structure (2/4)

- **QMBOC(6,1,4/33) : focus of the presentation**
  - Quadrature Multiplexed BOC
  - BOC(1,1) and BOC(6,1) are modulated on two quadrature phases, with same PRN code.



[1] Zheng Yao, Mingquan Lu, and Zhenming Feng, Quadrature multiplexed BOC modulation for interoperable GNSS signals, *Electronics Letters*, 2010, 46(17): 1234-1236.
[2] Mingquan Lu, Zheng Yao. New Signal Structures for BeiDou Navigation Satellite System, 10/29/2014, presentation at Stanford's 2014 PNT Symposium

B1C/B2a Signal Structure (3/4)

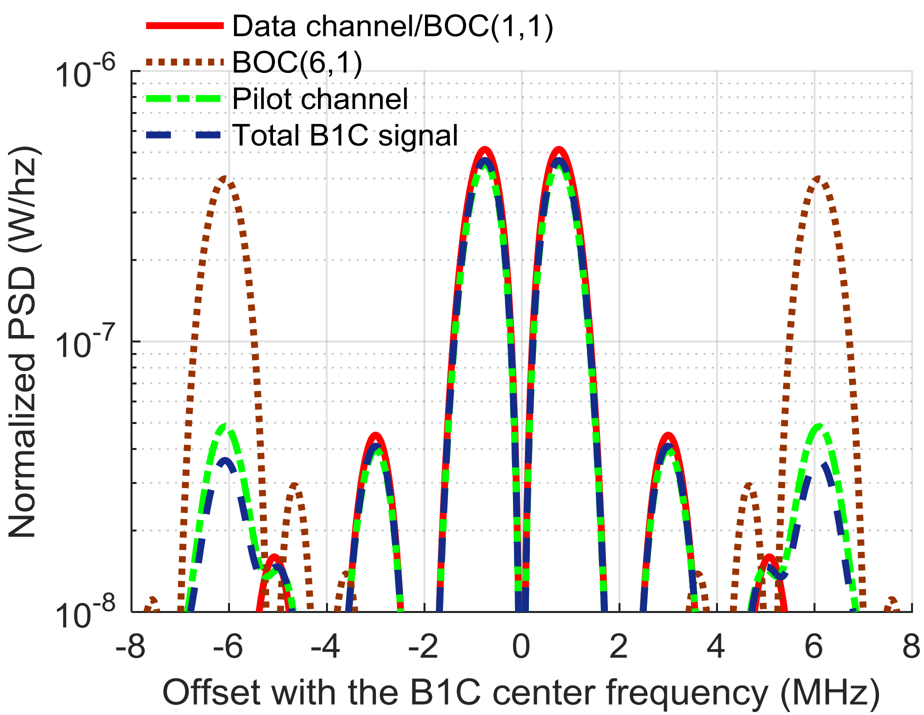
- **Comparison of three time-domain implementation of MBOC**

Modulation Method	Application	Number of Carrier Components	Code Chip Polarity	Code Chip Rate	Performance	Complexity in Receiver
QMBOC	BDS-3 B1C	Two	0 and 1	Unchanged	Similar	Similar
TMBOC	GPS L1C QZSS L1C	One	0 and 1	Changed with time		
CBOC	Galileo E1	One	Multiple polarities	Unchanged		

- **Implications (**To develop FPGA correlator needs**)**
  - Multi-level code polarities for CMBOC
  - Change code chip rate for TMBOC with time
  - Two local codes (BOC(1,1) & BOC(6,1)) for each QMBOC correlator

B1C/B2a Signal Structure (4/4)

- **Power Spectral Density (PSD) of the B1C signals**



- ☞ Similar performances as in GPS L1C and Galileo E1
- ☞ More robust to narrow-band RFI compared with B1I and B2I

Basic Processing Techniques of QMBOC Signals (1/2)

Two Approach to bandwidth, acquisition & tracking

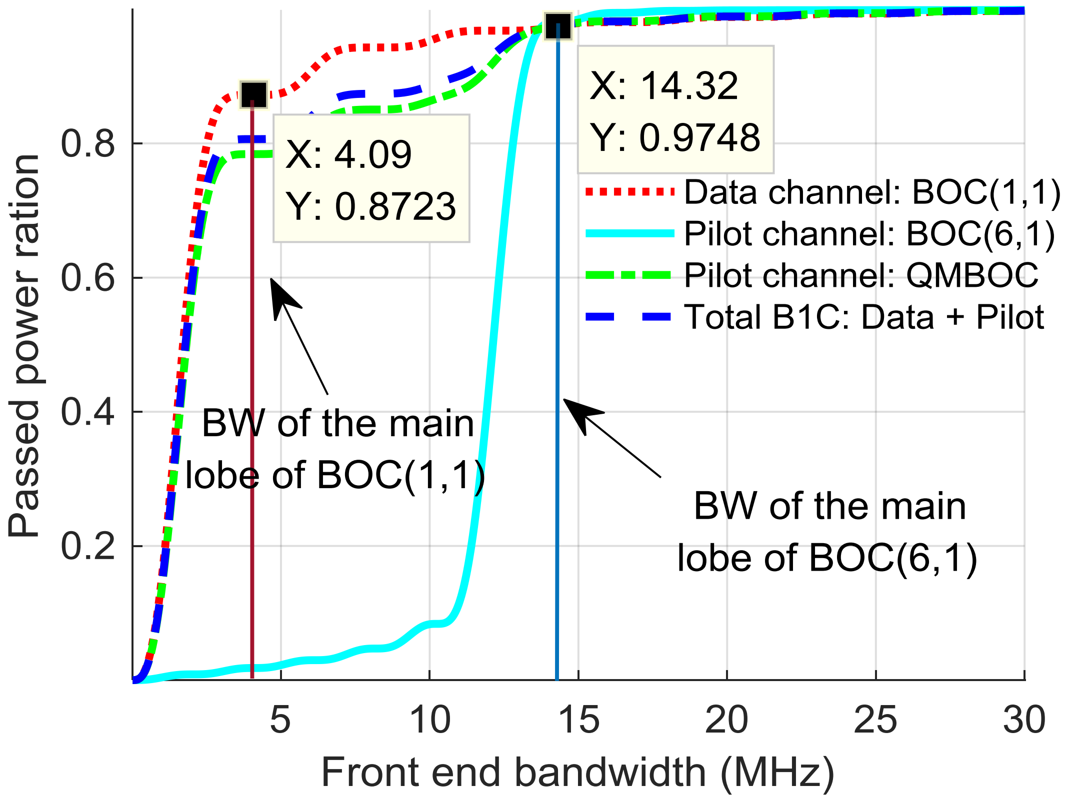
- Narrowband / unmatched method: Utilize BOC(1,1)- like
- Wideband / matched method – Utilize all signal components

Tracking method	Processed components	Front end BW	Sampling Frequency	Complexity	Accuracy	Multipath Rejection
Matched	BOC(1,1) + BOC(6,1)	High	High	High	High	High
Unmatched	BOC(1,1)	Low	Low	Low	Low	Low

[1] Mingquan Lu, Zheng Yao. New Signal Structures for BeiDou Navigation Satellite System, 10/29/2014, presentation at Stanford's 2014 PNT Symposium

Basic Processing Techniques of QMBOC Signals (2/2)

- **Power distribution of different components of B1C**

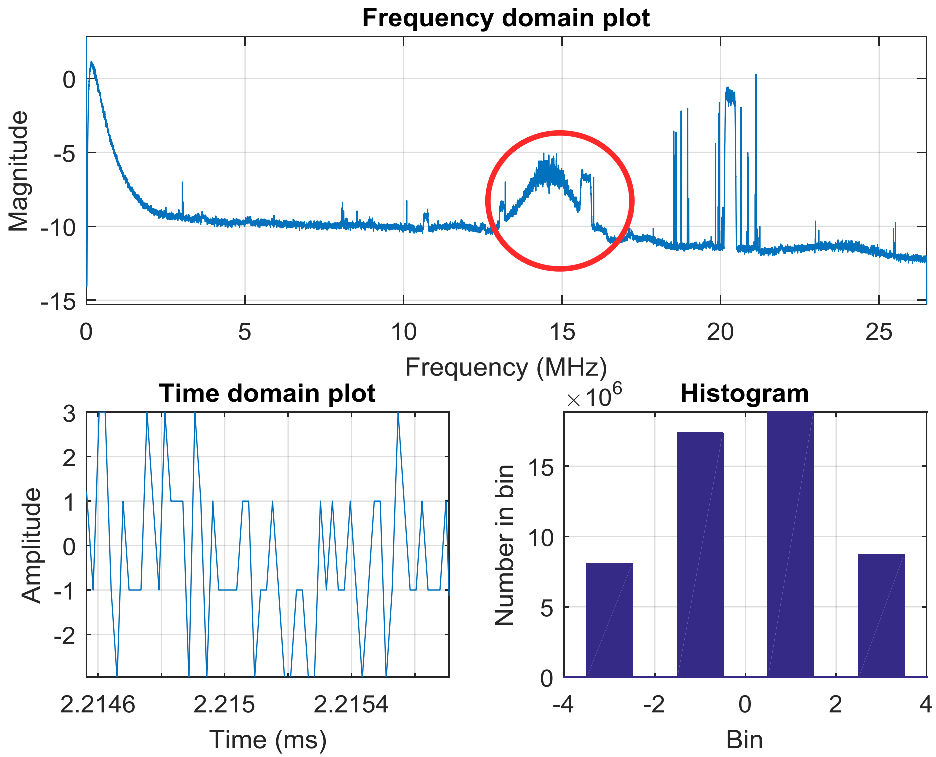


As long as the front-end BW is larger than 14.32 MHz, more than 97.5% power can be included.

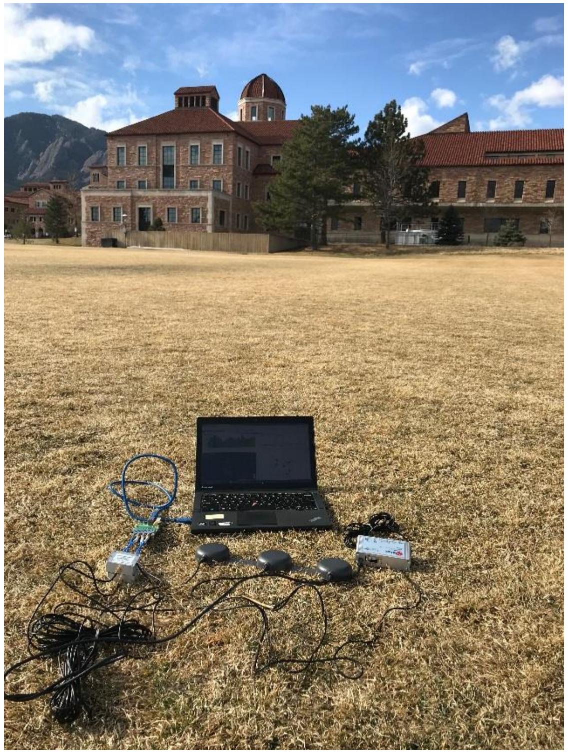
- BW of the main lobe (null-null)
  - BOC(1,1) : 4.092 MHz
  - QMBOC(6,1,4/33): 14.322 MHz

B1C SDR Structure and Captured Signals

- **Captured signals**



Spectrum (up), time-domain plot (lower-left), and bin distribution of the digitized IF samples



Signal collection using a 4-channel NUT4NT sampler

Signal Processing of the B1C SDR Receiver (1/13)

- Acquisition strategy
  - BOC(1,1)-like processing for QMBOC
  - Circular correlation by Zero-padding FFT

    - Avoid Nav bit and secondary code transition

    - Computation is doubled
  - Separate acquisition of data channel
  - Joint acquisition of both data and pilot channel

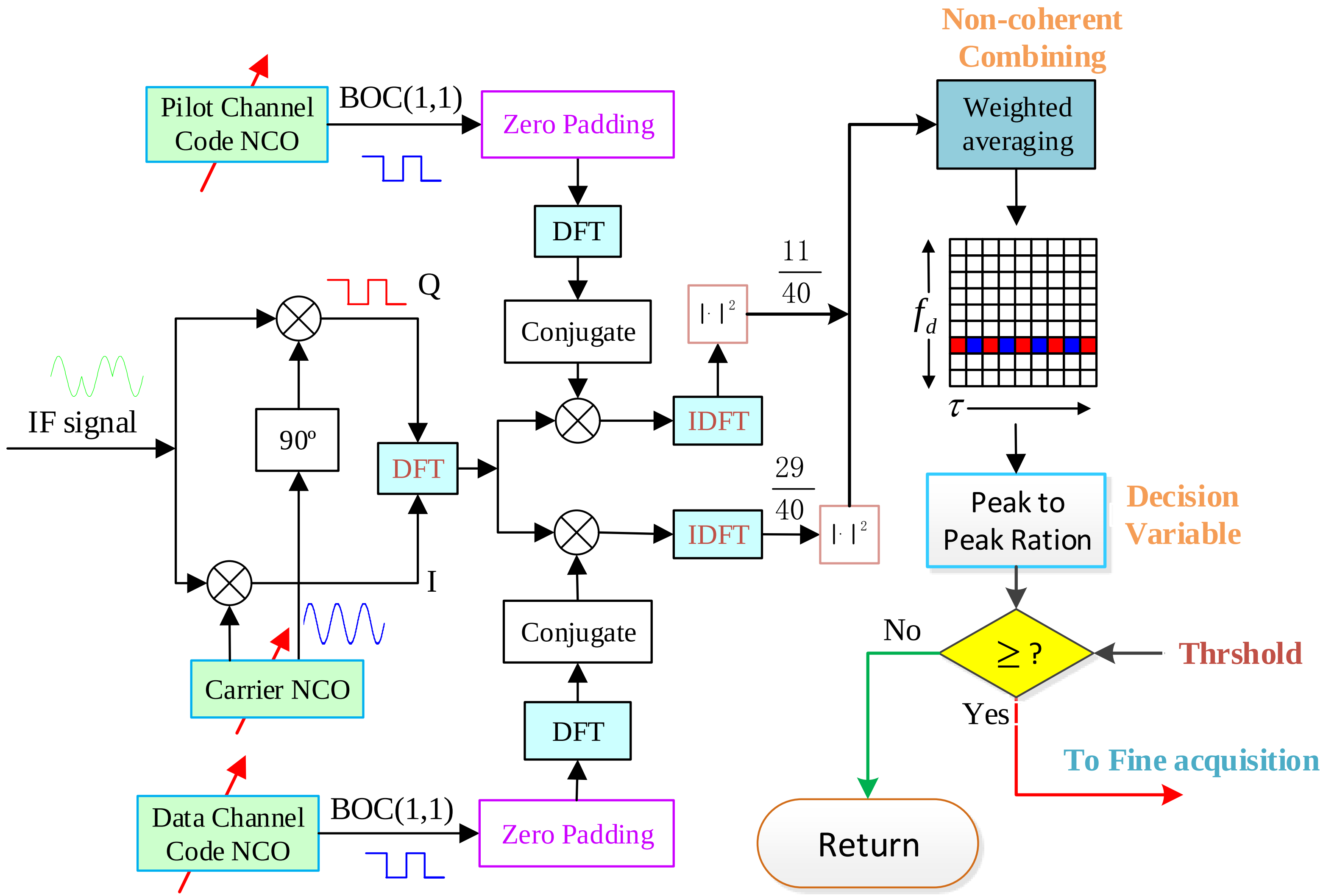
    - Non-coherent combination

    - Weighted averaging powers of two channels
  - Non-coherent searching for fine carrier frequency

    - Centered at the coarse carrier frequency acquired

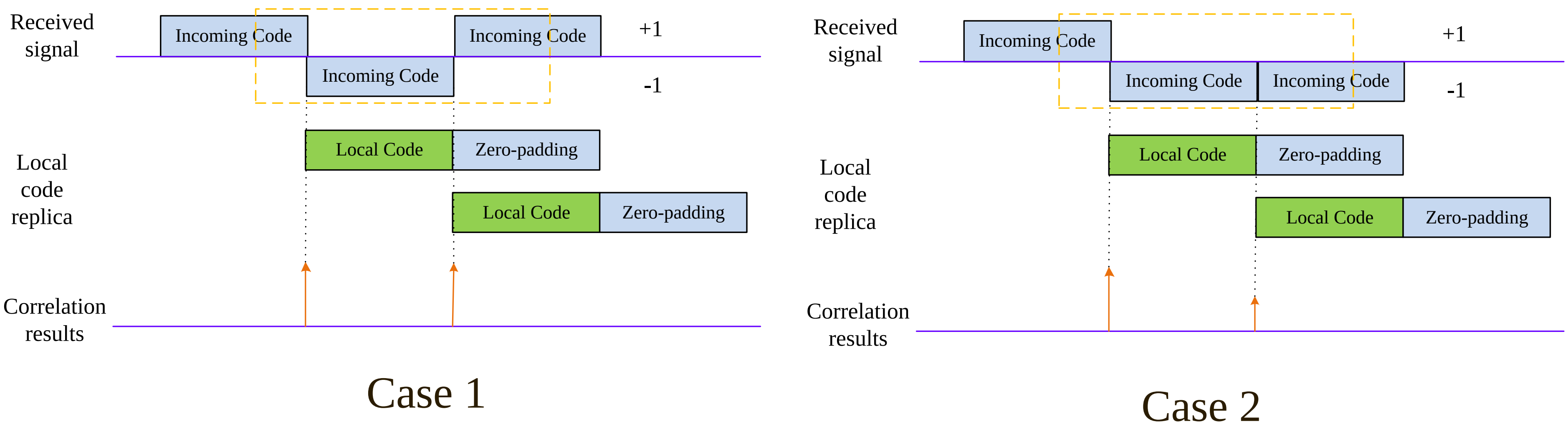
Signal Processing of the B1C SDR Receiver (2/13)

- Joint acquisition strategy (unmatched focus)



Signal Processing of the B1C SDR Receiver (3/13)

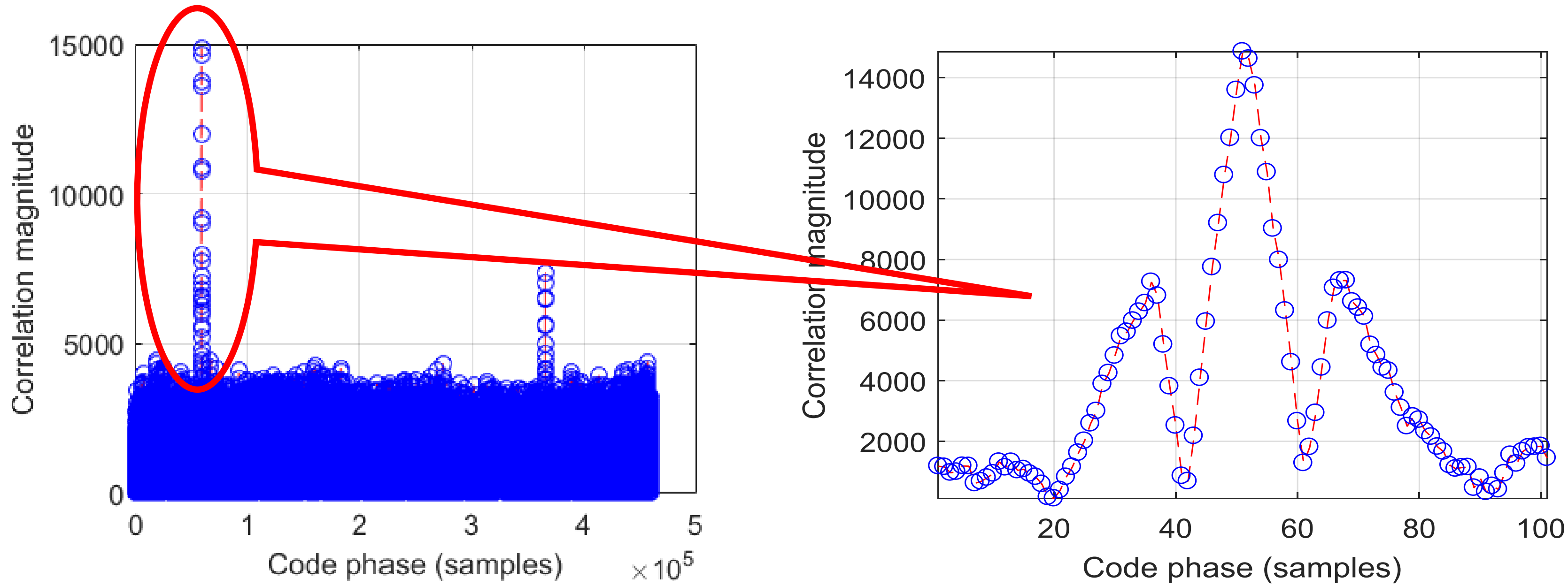
- Possible correlation results (data channel)



☞ Two peaks for each acquisition trial

Signal Processing of the B1C SDR Receiver (4/13)

- Acquisition results: data channel



Profile of the correlation result at the acquired Doppler bin

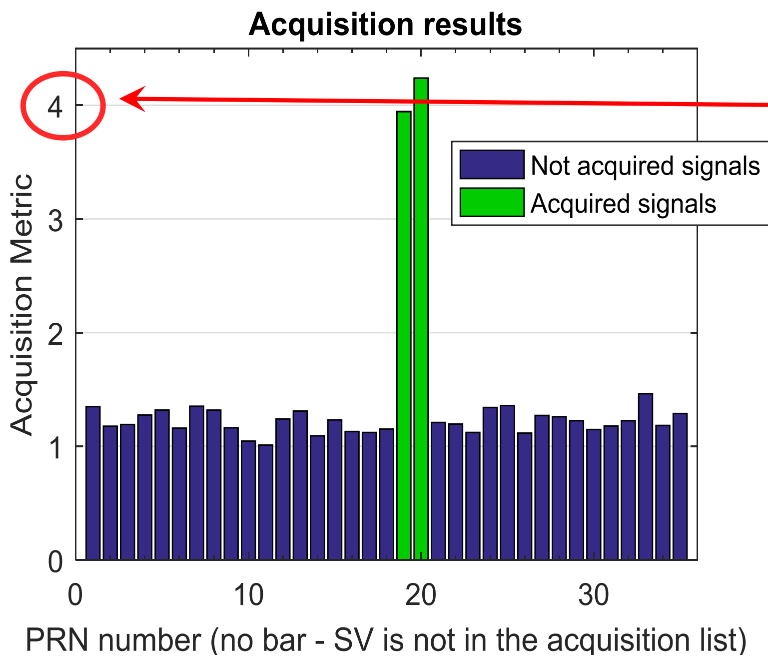
Zoomed-in correlation magnitude around the main peak group

☞ Multi-peak issue

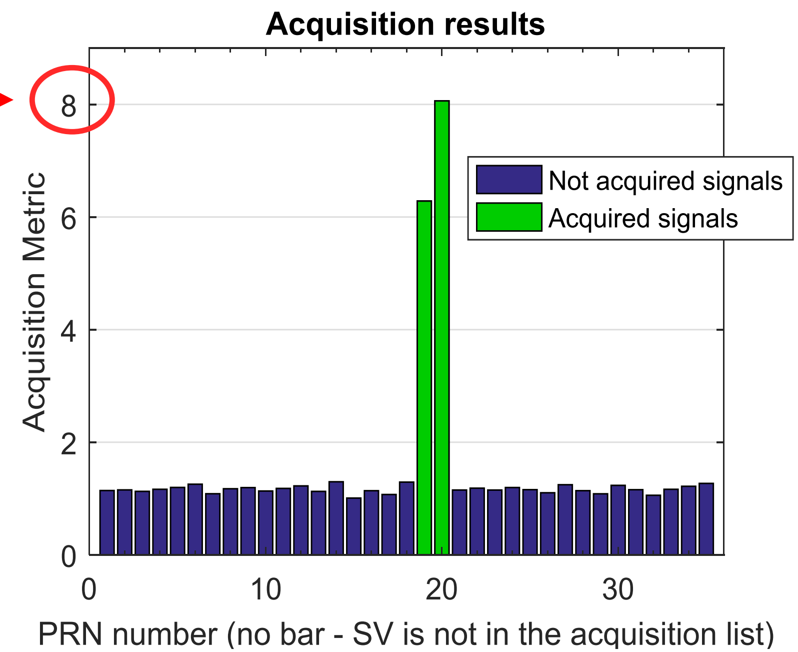
- **Unambiguous processing techniques**
- **Multiple approaches in the literature can be incorporated**

Signal Processing of the B1C SDR Receiver (5/13)

- Joint acquisition results: data and pilot channels



Data signal acquisition



Joint acquisition

☞ **Joint acquisition**

- **Higher acquisition metric**
- **Increased sensitivity and reliability**

Signal Processing of the B1C SDR Receiver (6/13)

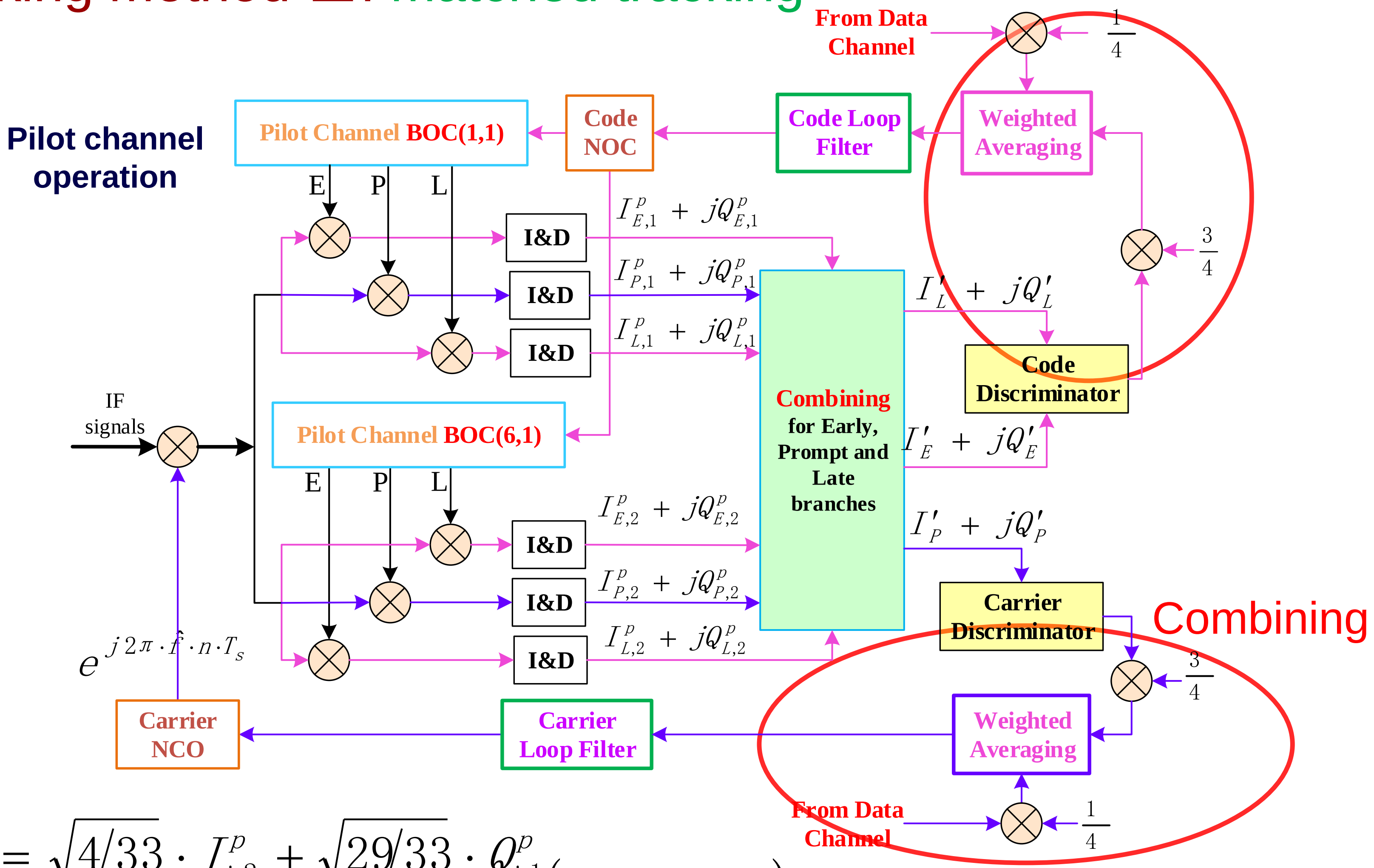
- Tracking method Ⅰ: unmatched tracking
  - Weighted averaging combining of discriminator outputs of data and pilot channels
  - BOC(1,1) like: does not consider ambiguous tracking issue (assumes higher signal power)

- Tracking method Ⅱ: matched tracking
  - Processes both the BOC(1,1) and BOC(6,1) components of QMBOC

Both versions are included in the open source SDR

Signal Processing of the B1C SDR Receiver (7/13)

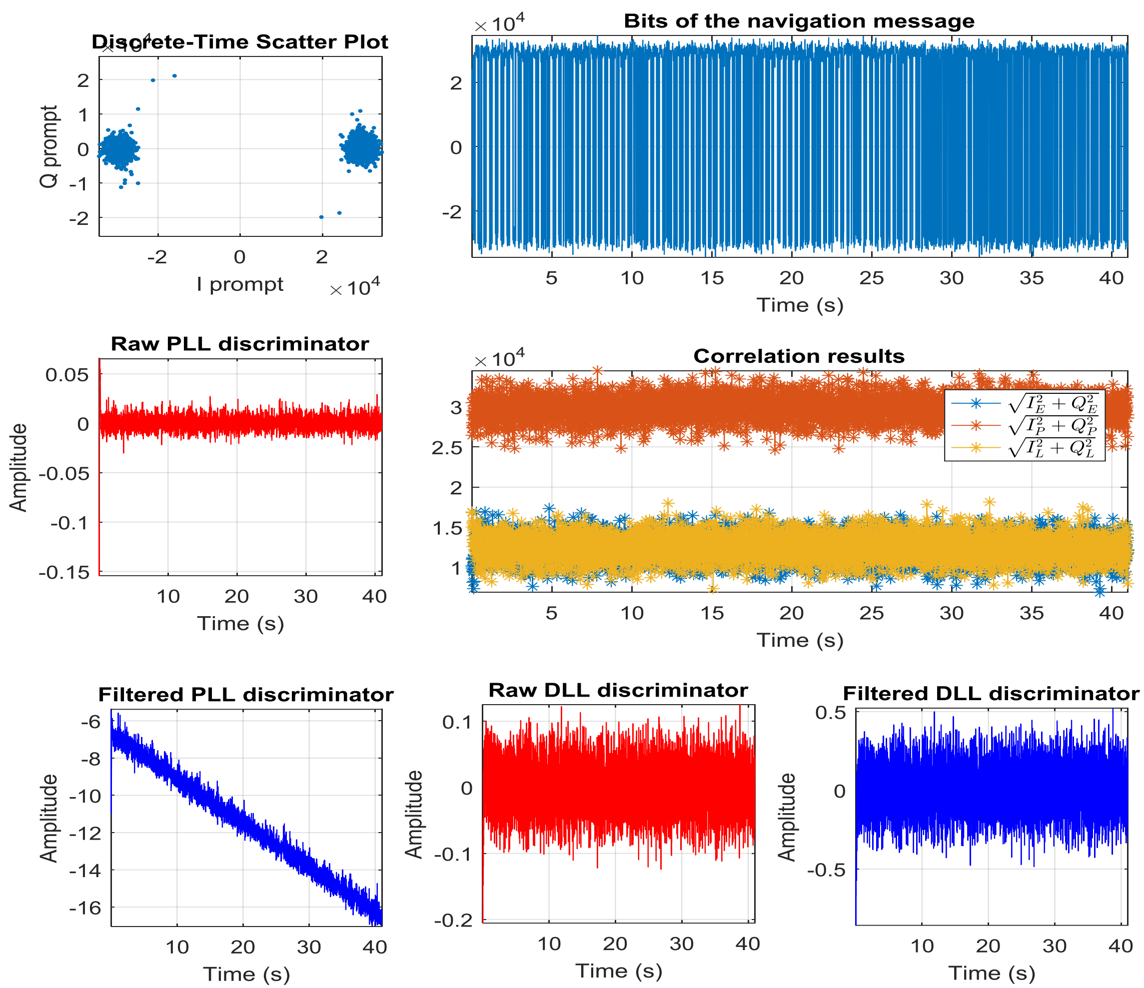
- Tracking method Ⅱ: matched tracking



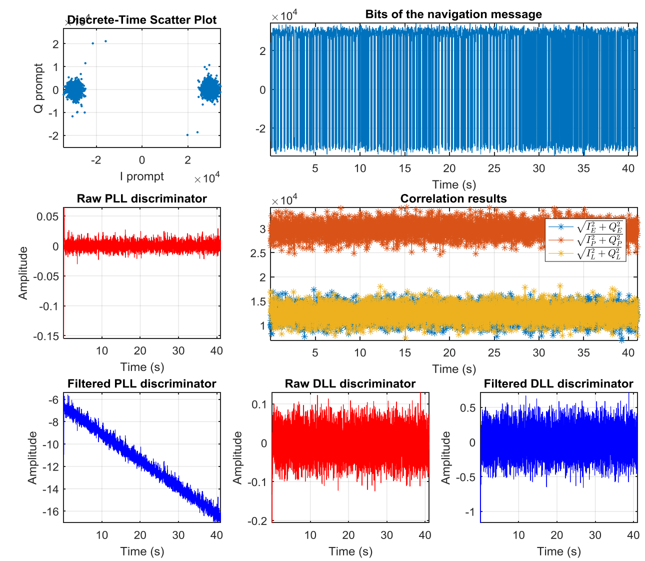
$$\begin{cases} I_*^p = \sqrt{4/33}\cdot I_{*,2}^p + \sqrt{29/33}\cdot Q_{*,1}^p \\ Q_*^p = \sqrt{4/33}\cdot Q_{*,2}^p - \sqrt{29/33}\cdot I_{*,1}^p \end{cases} (* = E, P, L)$$

Signal Processing of the B1C SDR Receiver (8/13)

- Matched tracking results of live signal



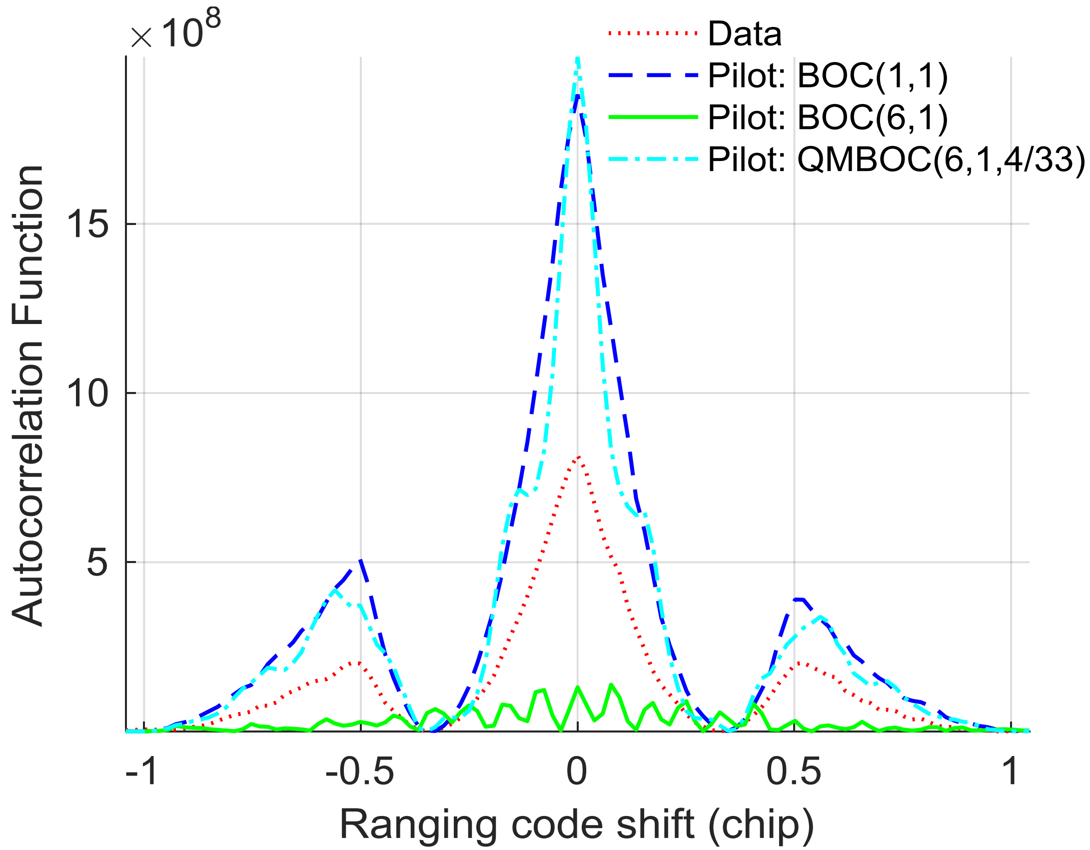
Matched tracking



Unmatched tracking

Signal Processing of the B1C SDR Receiver (9/13)

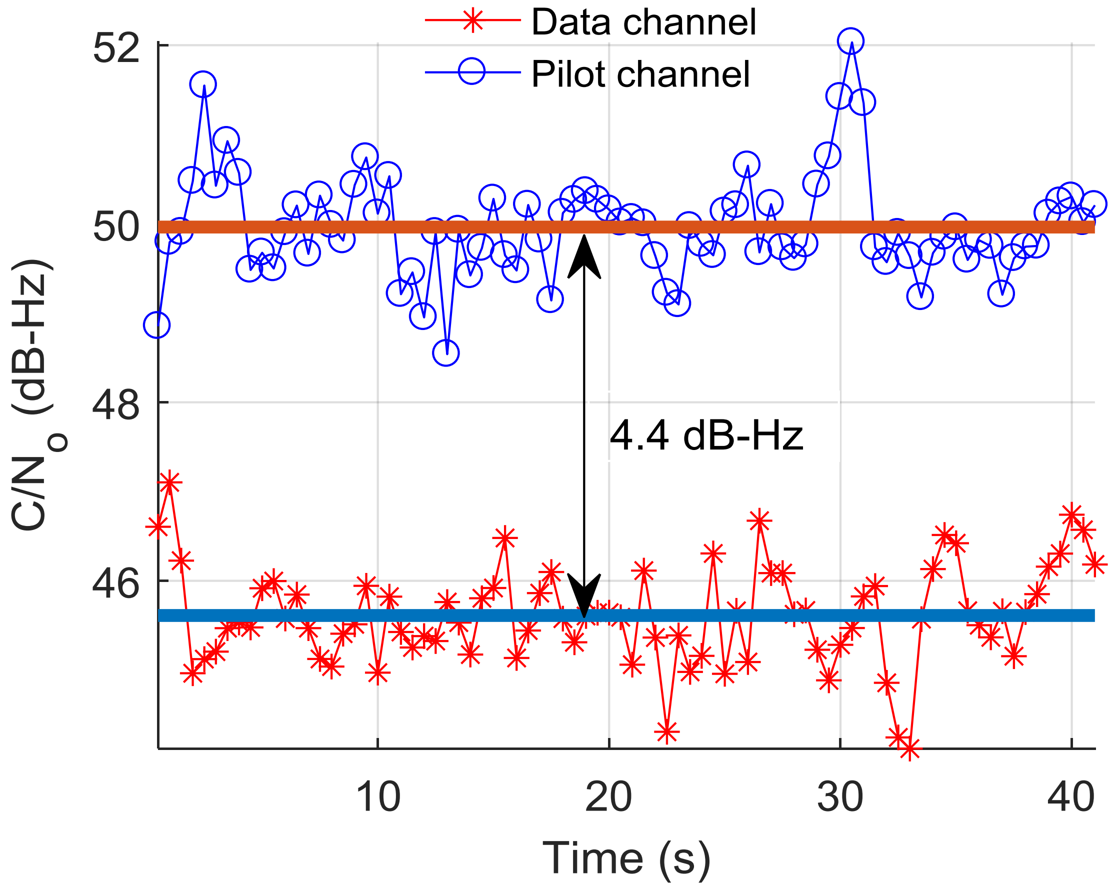
- Matched tracking results of **live** signal
  - Obtained by shifting tracked ranging coed phases



Autocorrelation functions obtained from live B1C signal (sampling frequency is 53 MHz)

Signal Processing of the B1C SDR Receiver (10/13)

- Tracking quality parameter calculation

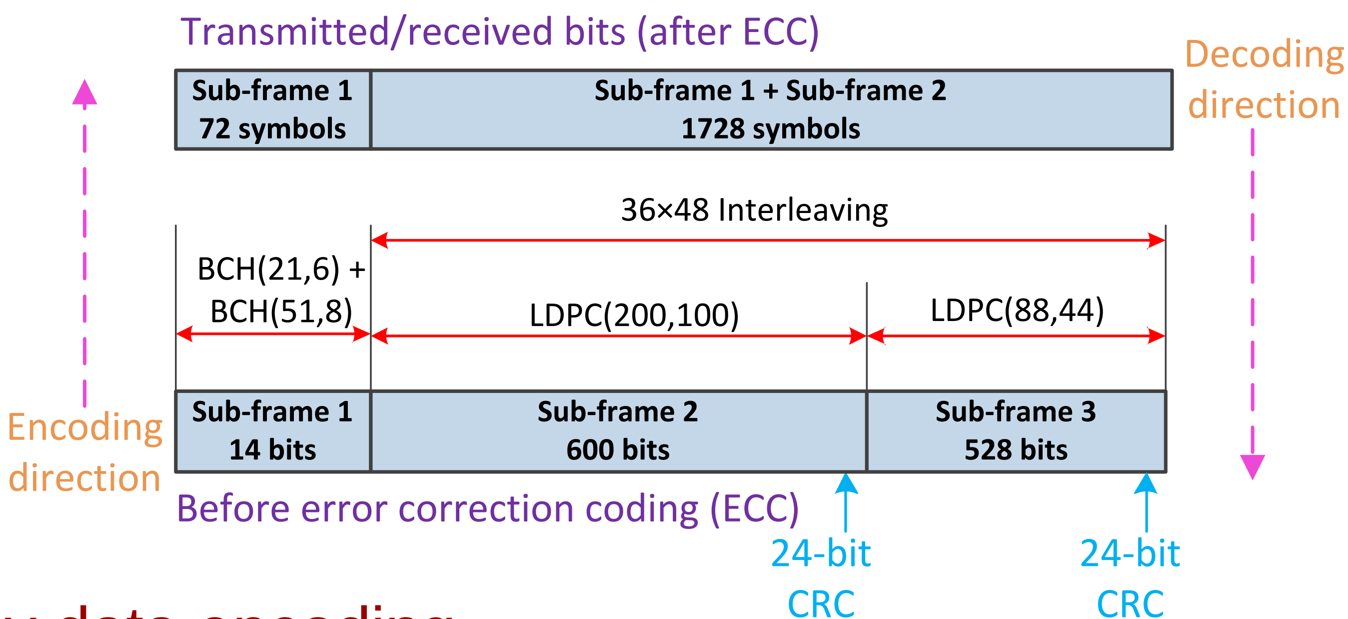


C/N_0 **estimations for data and pilot channels (unmatched tracking)**

☞ The nominal C/N_0 difference between the pilot and data channels are 4.2 dB-Hz in unmatched tracking.

Signal Processing of the B1C SDR Receiver (11/13)

- Navigation data decoding



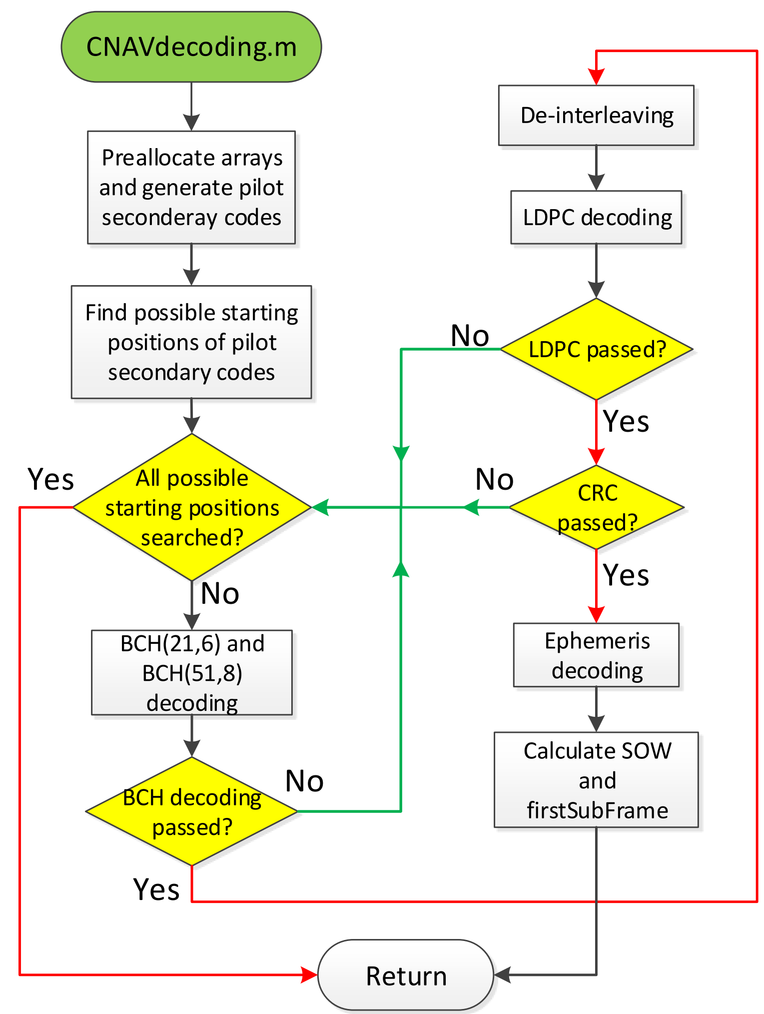
- Nav data encoding
  - 24-bit Cyclical Redundancy Check (CRC-24)
  - Bose–Chaudhuri–Hocquenghem (BCH) codes,
  - Interleaving
  - Low-Density Parity-Check (LDPC)
- Nav data decoding: in reverse order

Signal Processing of the B1C SDR Receiver (12/13)

- Navigation data decoding
  - No preamble sequences for frame synchronization

Possible solutions

1. Do BCH(21,6) decoding bit by bit for the first sub-frame until BCH passes
   - **time consuming**
2. Find the first secondary code chip of the pilot signals



Flow diagram for NAV data decoding

Signal Processing of the B1C SDR Receiver (13/13)

PVT calculation

- Implemented SDR is capable of PVT solution calculation
  - The Health Status (HS) of the BDS-3 SVs are still flagged with “unhealthy” as of Jan. 17, 2018.
  - NO PVT can be obtained as of Jan. 17, 2018!

Variables - eph

eph

2	T_GDB2ap	ISC_E	T_GDB1(	PageID	HS	DIF	SIF	AIF	SISMAI	alpha1	alpha2	alpha3	alp
[]	[]	[]	[]	[	[]	[]	[]	[]	[]	[]	[]	[]	
0	0	0	0	4	2	0	0	0	1	[]	[]	[]	
e-...	-1.1915e-07	-1.1915...	-1.1915e-07	4	2	0	0	0	1	[]	[]	[]	

Future Work and Improvement

- **Increase processing speed**
  - Realize correlators by Single Instruction Multiple Data (SIMD) or GPU
  - Run Dynamic Link Library (DLL) for correlators in Matlab
- **Retain the easy-to-use feature of Matlab for education and algorithm research**
- **Incorporate new signals and support regional navigation and augmentation systems**
  - GPS L1C
  - GLONASS CDMA signals
  - SBAS, QZSS, IRNSS

Thank you!

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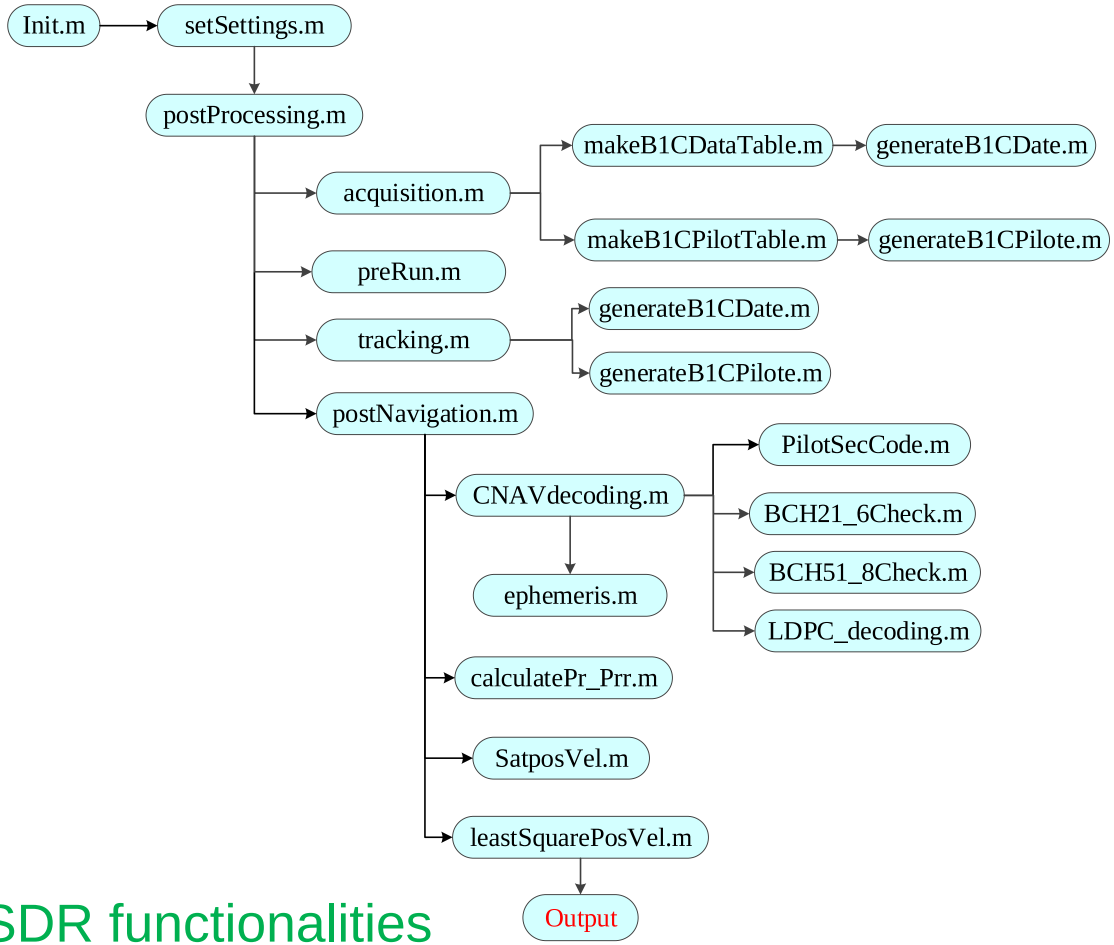
B1C SDR Structure and Captured Signals (1/2)

- **Top-level B1C SDR structure**



- Complete SDR functionalities

  - PSD plot, acquisition, tracking, NAV data decoding, measurement generation, calculation of Position, Velocity and Time (PVT)

Signal Processing of the B1C SDR Receiver (7/17)

- Tracking method Ⅰ: unmatched tracking
  - Weighted averaging combining of discriminator outputs of data and pilot channels
  - BOC(1,1) like: does not consider ambiguous tracking issue (assumes higher signal power)

Signal Processing of the B1C SDR Receiver (8/17)

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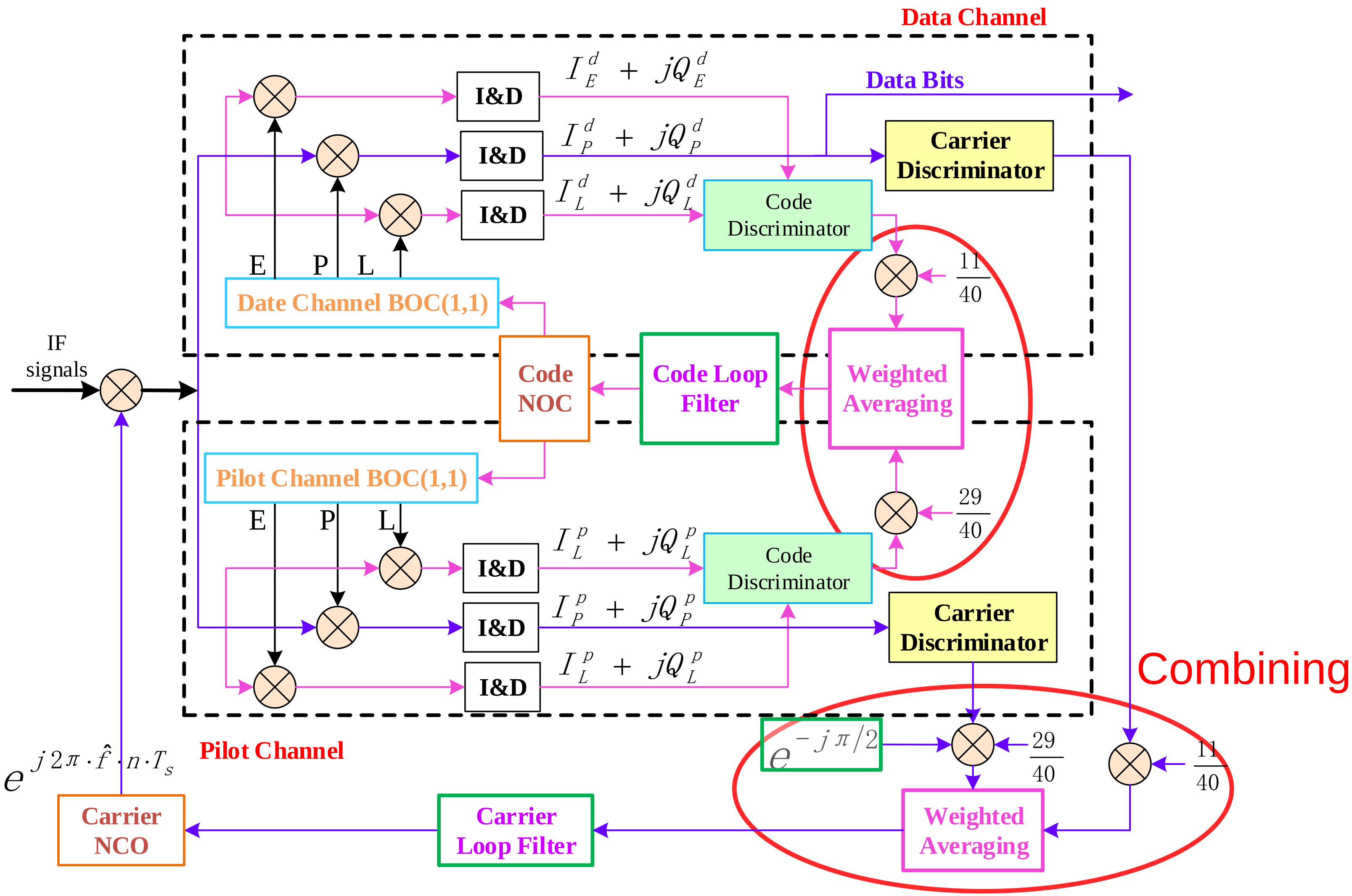
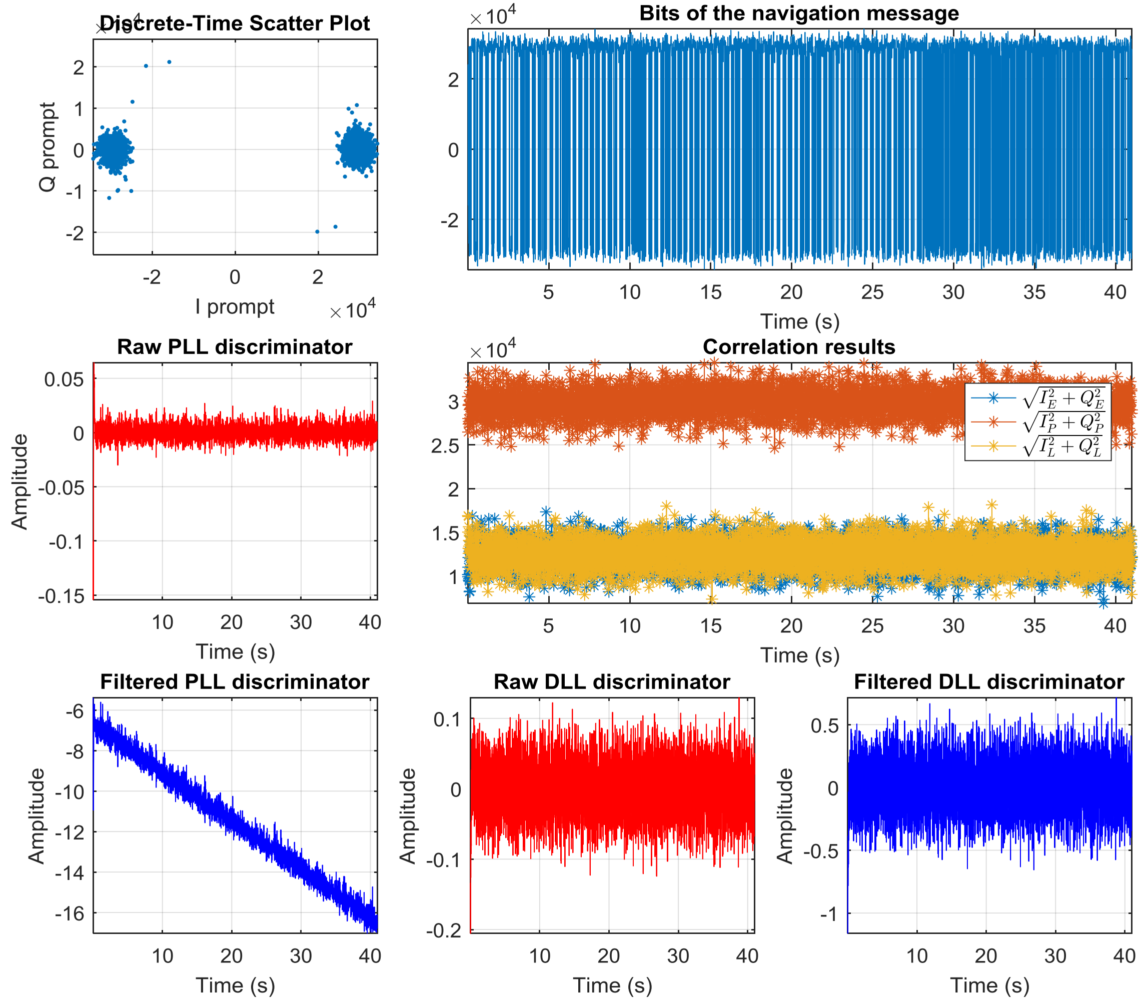


Signal Processing of the B1C SDR Receiver (9/17)

- Unmatched tracking results of live signal



Data channel of PRN # 19