2025年度 測位航法学会 全国大会 セミナー④

GNSS SDRの設計、実装と応用

- Pocket SDRを例題にして

Design, Implementation and Application of GNSS SDR

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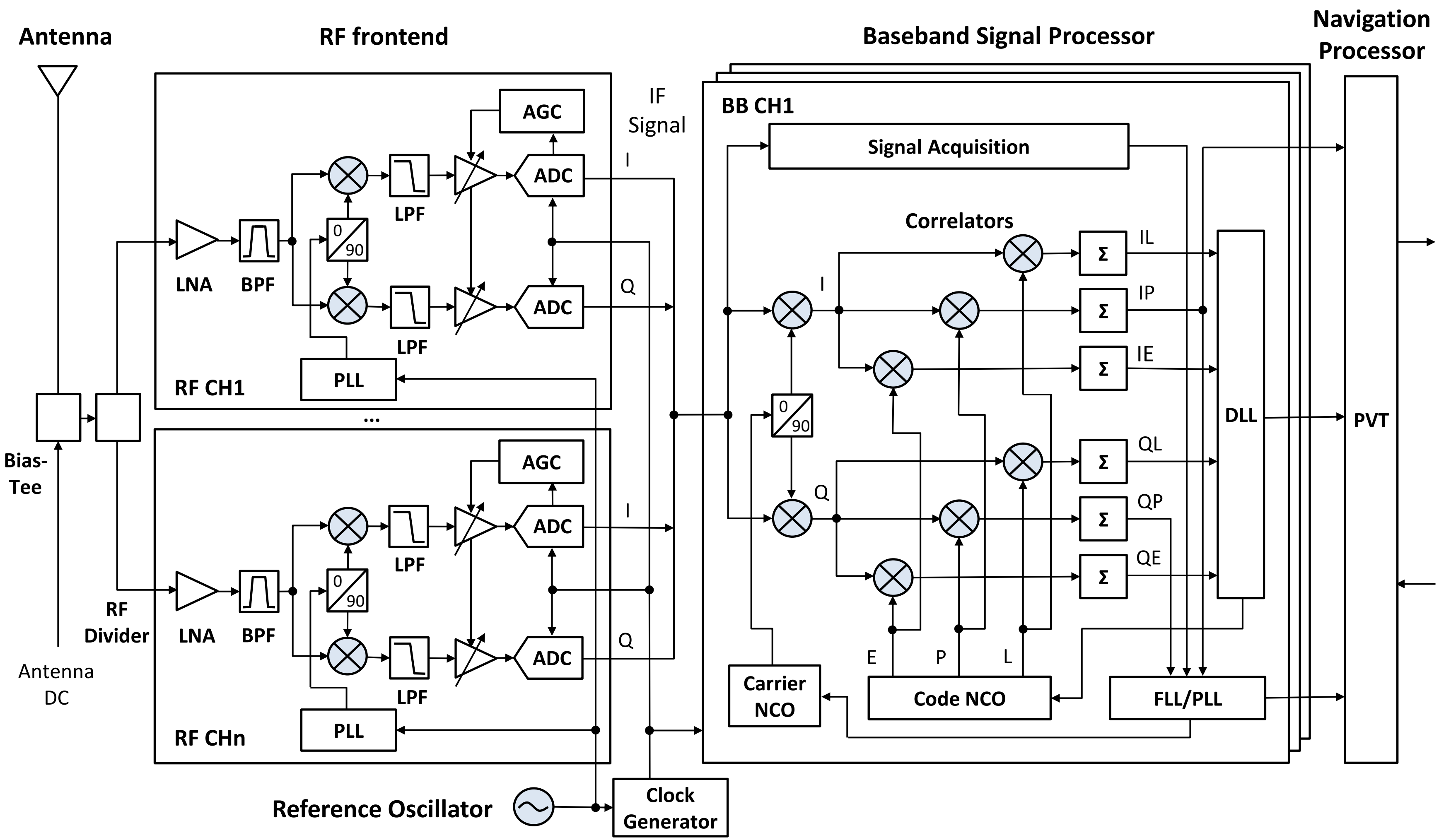
Rev.A 2025-05-22

Time Table

- **9:30 - 10:10 Introduction of Pocket SDR**
- **10:10 - 10:30 Modernized GNSS Signals**
- **10:40 - 11:30 RF Frontend**
- **11:30 - 12:30 Baseband Signal Processor**
- **12:30 - 13:30 Lunch break**
- **13:30 - 14:00 Navigation Processor**
- **14:00 - 15:00 Implementation of Pocket SDR**
- **15:10 - 16:30 Applications of GNSS SDR**

Introduction of Pocket SDR

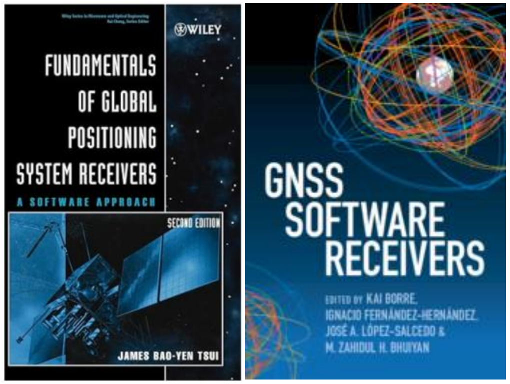
GNSS Receiver



LNA: low noise amplifier, BPF: bandpass filter, LPF: lowpass filter, ADC: analog digital converter, AGC: automatic gain control, IF: intermediate frequency, PLL: phase lock loop, DLL: delay lock loop, FLL: frequency lock loop, NCO: numerical controlled oscillator, LDPC: low density parity check code, RS: Reed Solomon code, PVT: position, velocity and time

GNSS SDR

- **SDR (Software Defined Radio)**
  - RF Signal Processing by FPGA, DSP, GPP (CPU) or GPU instead of H/W circuits
  - RF-frontend: USRP (Universal Software Radio Peripheral) [1], RTL-SDR [2], ...
  - S/W: GNU Radio [3], LabVIEW [4], MATLAB/Simlink [5], ...
  - Applications: radio/TV, mobile comm. (WiFi, BT, LTE, ...), radar, measuring instrument, GNSS, ...
  - PROS: fast system development, high flexibility by S/W modification, easy upgrade by CPU replacement, good tool for research, education and training, ...
  - CONS: limited sampling rate, narrow BW, high power consumption, large size, heavy weight, ...
- **GNSS SDR (Software Defined Receiver)** [6]
  - GNSS Receiver implemented by SDR
  - RF-frontend H/W (+ FPGA) + S/W codes
  - Post-processing or real-time
  - Programming Languages: C/C++, MATLAB, python, ...
- **GNSS SDR Textbooks**
  - J. B-Y. Tsui, Fundamentals of Global Positioning System Receivers: A Software Approach, 2000, John Wiley & Sons [7]
  - K. Borre et al. (ed.), GNSS Software Receivers, 2023, Cambridge University Press [8]



[1] https://www.ettus.com, [2] https://rtl-sdr.com/, [3] https://www.gnuradio.org, [4] https://www.ni.com/en/shop/labview.html,
[5] https://www.mathworks.com, [6] https://en.wikipedia.org/wiki/GNSS_software-defined_receiver,
[7] https://onlinelibrary.wiley.com/doi/book/10.1002/0471712582,
[8] https://www.cambridge.org/core/books/gnss-software-receivers/7F2858B9EC73EBD40A07602966878430

OSS GNSS SDR

Software		GNSS-SDR	GNSS-SDRLIB	Pocket SDR
URL		https://gnss-sdr.org https://github.com/gnss-sdr	https://github.com/taroz/GNSS-SDRLIB	https://github.com/tomojitakasu/PocketSDR
Current Release		v0.0.20 (April 2025)	v2.0 Beta (Dec 2014)	ver. 0.14 (March 2025)
License		GPL-3.0	GPL-2 or later	BSD 2-clause
GitHub Stars/Forks		☆ 1.8k / 639	☆ 487 / 177	☆ 356 / 111
Processing Mode		Post Processing, Real-time	Post Processing, Real-time	Post Processing, Real-time
PVT		Single, PPP	-	Single
Output Format		KML, GeoJSON, GPX, RINEX, NMEA, RTCM3, Custom	RTCM3, RINEX	NMEA, RTCM3, CSV Log, Raw binary
Supported GNSS Signals	GPS	L1C/A, L2C, L5	L1C/A	L1C/A, L1C, L2C, L5
	GLONASS	L1C/A, L2C/A	L1C/A	L1C/A, L2C/A, L1OC, L2OC, L3OC
	Galileo	E1B/C, E5a, E5b, E6B	E1B	E1B/C, E5a, E5b, E6B/C
	QZSS	-	L1C/A, L1SAIF, LEX	L1C/A, L1C/B, L1C, L1S, L2C, L5, L5S, L6D/E
	BeiDou	B1I, B3I	B1I	B1I, B1C, B2I, B2a, B2b, B3I
	NavIC	-	-	L1-SPS, L5-SPS (,S-SPS)
	SBAS	-	L1C/A	L1C/A, L5
Supported RF frontends		USRP, UmTRX, HackRF One, Blade RF, RTL-SDR	SiGe GN3S sampler v2/v3, Stereo, Blade RF, RTL-SDR	Pocket SDR FE 2/4/8CH
OS		Linux, macOS	Windows, Linux	Windows, Linux, macOS, Raspberry Pi OS
Programming Language		C++, C	C, C++/CLI	Python 3, C++, C
External Libraries		GNU Radio, Boost, FFTW3, VOLK, Armadillo, LAPACK/BLAS, glog, gflags, matio, pugiXML, Protocol Buffers, OpenSSL, RTKLIB	FFTW3, LIBFEC, RTKLIB, libusb	FFTW3, LIBFEC, LDPC-codes, RTKLIB, CyAPI or libusb-1.0

Pocket SDR

tomojitakasu / PocketSDR

Code | Issues 16 | Pull requests 5 | Discussions | Actions | Projects | Wiki | Security | Insights

PocketSDR Public

master | 1 Branch | 0 Tags

tomojitakasu Fixed #39. f9826b6 · last month 898 Commits

FE_2CH	Updated.	2 months ago
FE_4CH	Updated.	2 months ago
FE_8CH	Updated.	2 months ago
app	Fix segfault.	2 months ago
bin	Updated.	last month
conf	CRLF->LF.	2 months ago
doc	Updated.	2 months ago
driver	Updated.	4 months ago
image	Added.	2 months ago
lib	Updated.	last month
python	Fixed #39.	last month
sample	http -> https.	2 months ago
src	Fixed segfault for INT8X2 format input.	last month
test	CRLF->LF.	2 months ago

History

- **2021-10-20 (v0.1)**: Initial draft version.
- **2021-10-25 (v0.2)**: Added rebuild firmware and write firmware image to Pocket SDR.
- **2021-12-01 (v0.3)**: Added and modified Python scripts.
- **2021-12-25 (v0.4)**: Added and modified Python scripts.
- **2022-01-05 (v0.5)**: Fixed several issues.
- **2022-01-13 (v0.6)**: Added and modified Python scripts.
- **2022-02-15 (v0.7)**: Improved performance and added more Python scripts.
- **2022-07-08 (v0.8)**: Added C-version of pocket_acq.py and pocket_trk.py.
- **2024-01-03 (v0.9)**: Added C-version of pocket_snap.py. pocket_trk now supports multi-signal and multi-threading.
- **2024-01-12 (v0.10)**: Added support for NavIC L1-SPS-D, L1-SPS-P, GLONASS L1OCd, L1OCp, and L2OCp.
- **2024-01-25 (v0.11)**: Added support for decoding GLONASS L1OCd NAV data and NB-LDPC error correction for BDS B1C, B2a, and B2b.
- **2024-05-28 (v0.12)**: Performance optimizations. Added support for PVT generation, RTCM3, and NMEA outputs.
- **2024-07-04 (v0.13)**: Added GUI-based GNSS SDR receiver AP. Added support for macOS and Raspberry Pi OS.
- **2025-03-21 (v0.14)**: Added Pocket SDR FE 8CH. Fixed various issues.

README | License

Pocket SDR - An Open-Source GNSS SDR, ver. 0.14

Overview

Pocket SDR is an open-source Global Navigation Satellite System (GNSS) receiver based on software-defined radio (SDR) technology. It consists of RF frontend devices named **Pocket SDR FE**, utilities for these devices, and GNSS SDR applications (APs) written in Python, C, and C++. It supports almost all signals for **GPS**, **GLONASS**, **Galileo**, **QZSS**, **BeiDou**, **NavIC**, and **SBAS**.

The Pocket SDR FE device includes 2, 4, or 8 RF frontend channels, supporting the GNSS L1 band (1525 - 1610 MHz) or L2/L5/L6 bands (1160 - 1290 MHz). For these signal bands, refer to GNSS Signal Bands. Each RF channel of the Pocket SDR FE device provides IF (intermediate-frequency) bandwidth of up to 36 MHz. The ADC sampling rate can be configured up to 32 Msps (FE 2CH) or 48 Msps (FE 4CH and FE 8CH).

Pocket SDR also includes utility programs to configure the Pocket SDR FE devices, capture, and dump digitized IF data. Additionally, Pocket SDR provides GNSS SDR APs to display the PSD (power spectrum density) of captured IF data, search for GNSS signals, track these signals, decode navigation data, and generate PVT (position, velocity, and time) solutions. These utilities and APs are compatible with **Windows**, **Linux**, **Raspberry Pi OS**, **macOS**, and other environments.

The supported GNSS signals by Pocket SDR are as follows. For details on these signals and Pocket SDR signal IDs, refer to GNSS Signals.

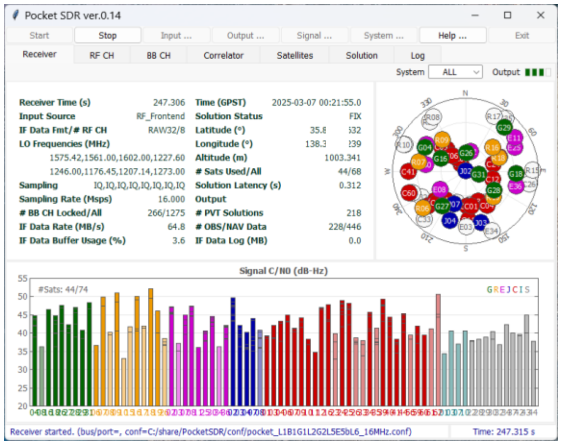
- **GPS**: L1C/A, L1C-D, L1C-P, L2C-M, L5-I, L5-Q
- **GLONASS**: L1C/A (L1OF), L2C/A (L2OF), L1OCd, L1OCp, L2OCp, L3OCd, L3OCp
- **Galileo**: E1-B, E1-C, E5a-I, E5a-Q, E5b-I, E5b-Q, E6-B, E6-C
- **QZSS**: L1C/A, L1C/B, L1C-D, L1C-P, L1S, L2C-M, L5-I, L5-Q, L5S-I, L5S-Q, L6D, L6E
- **BeiDou**: B1I, B1C-D, B1C-P, B2a-D, B2a-P, B2I, B2b-I, B3I
- **NavIC**: L1-SPS-D, L1-SPS-P, L5-SPS
- **SBAS**: L1C/A, L5-I, L5-Q

These utilities and APs are written in Python, C, and C++ in a compact and modular way, making them easy to modify for adding custom algorithms.

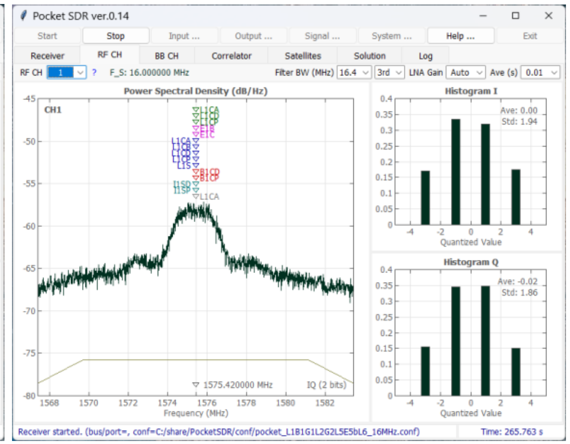
https://github.com/tomojitakasu/PocketSDR

GNSS Receiver (pocket_sdr.py) (1/3)

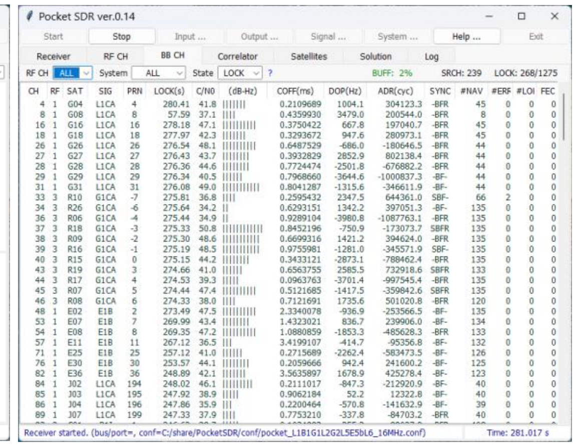
Receiver Tab



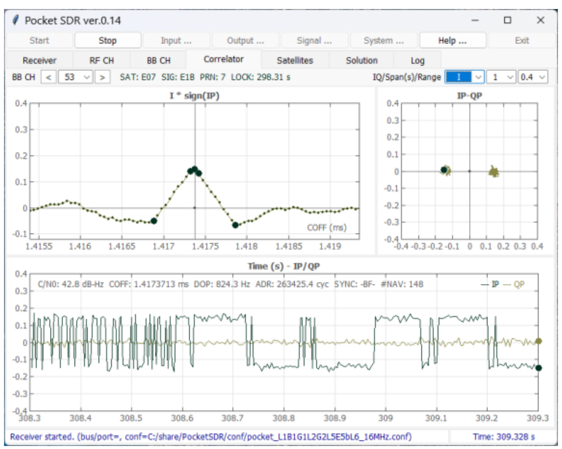
RF CH Tab



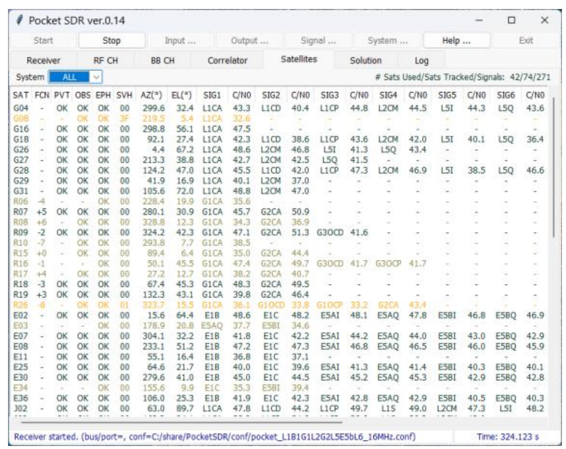
BB CH Tab



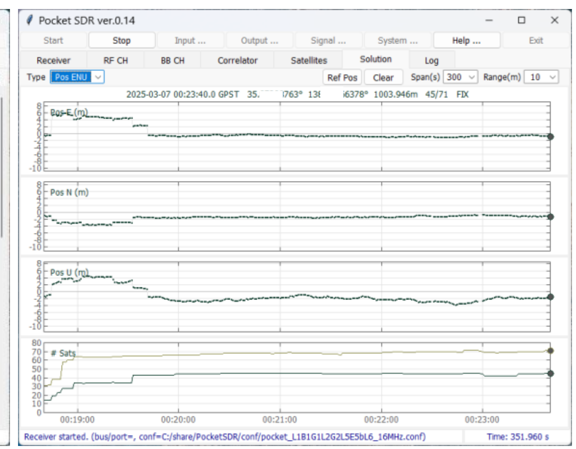
Correlator Tab



Satellites Tab

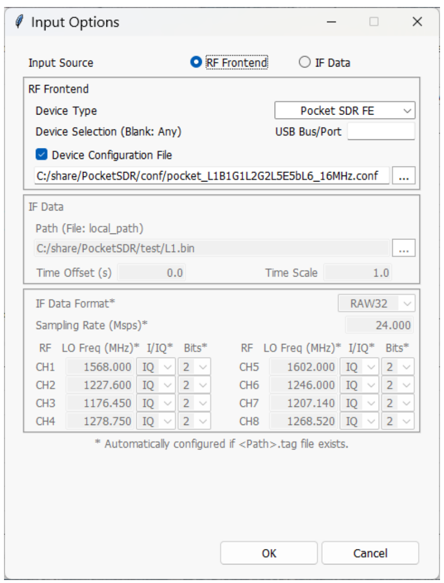


Solution Tab

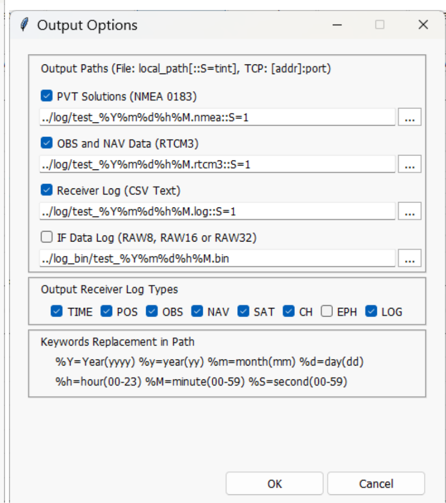


GNSS Receiver (pocket_sdr.py) (2/3)

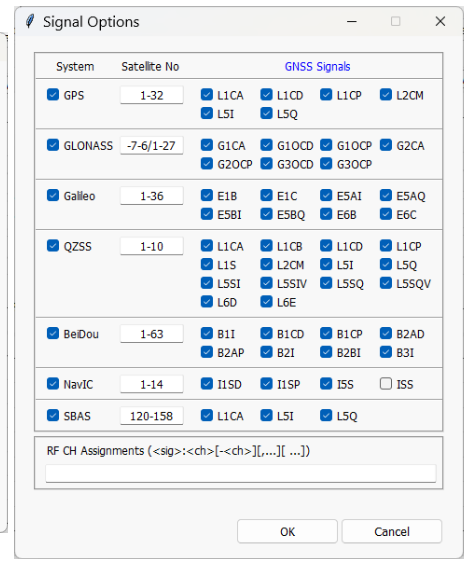
Input Options Dialog



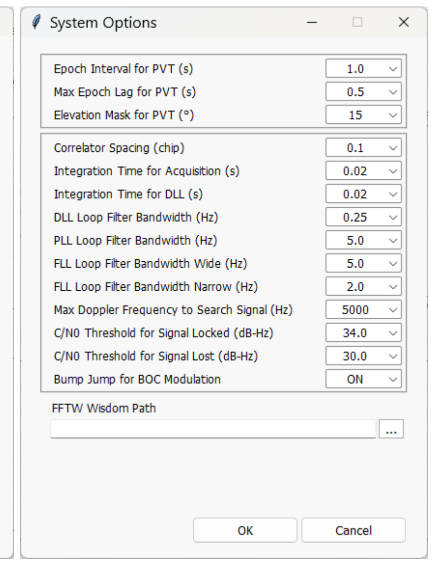
Output Options Dialog



Signal Options Dialog

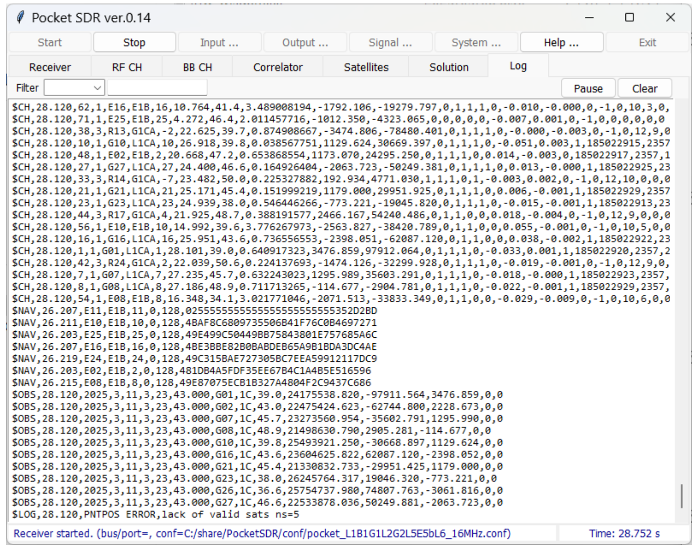


System Options Dialog



GNSS Receiver (pocket_sdr.py) (3/3)

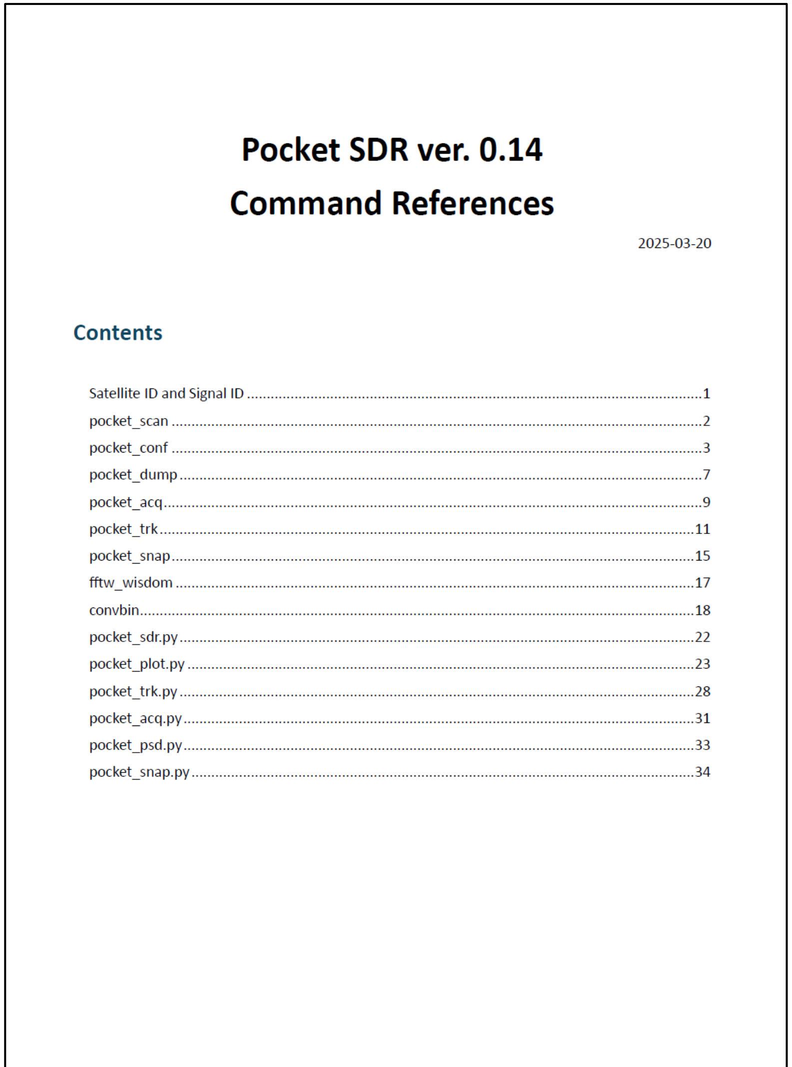
Log Tab



Receiver Logs

```
$TIME,time,year,mon,day,hour,min,sec,tsys (time info)
$OBS,time,year,month,day,hour,min,sec,sat,code,cn0,pr,cp,dop,lli,fcn (OBS data)
$NAV,time,sat,sig,nerr,size,data (raw NAV data HEX dump)
$POS,time,year,month,day,hour,min,sec,lat,lon,hgt,Q,ns,stdn,stde,stdu,dtr (position solution)
$SAT,time,year,month,day,hour,min,sec,sat,pvt,obs,cn0,az,el,res (satellite info)
$EPH,time,sat,sig,IODE,IODC,SVA,SVH,Toe,Toc,Ttr,A,e,i0,OMEGA0,omega,M0,delta-n,OMEGAdot,Idot,Crc,Crs,Cuc,Cus,Cic,Cis,Toes,
  Fit,Af0,Af1,Af2,TGD,code,flag (decoded ephemeris)
$CH,time,ch,rfch,sat,sig,prn,lock,cn0,coff,dop,adr,ssync,bsync,fsync,rev,srev,err_phas,err_code,tow_v,tow,week,type,nnav,
  nerr,nlol,nfec (receiver channel info)
$LOG,time,message (error, warning, general info message)
```

Pocket SDR Documents



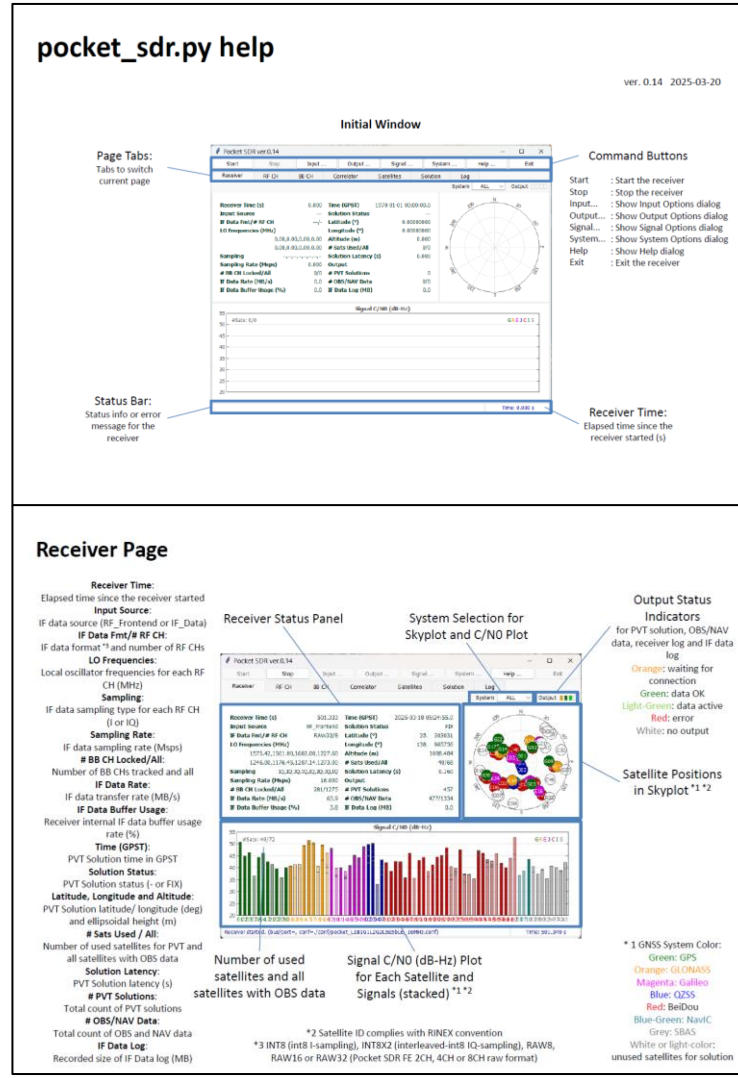
Pocket SDR ver. 0.14

Command References

2025-03-20

Contents

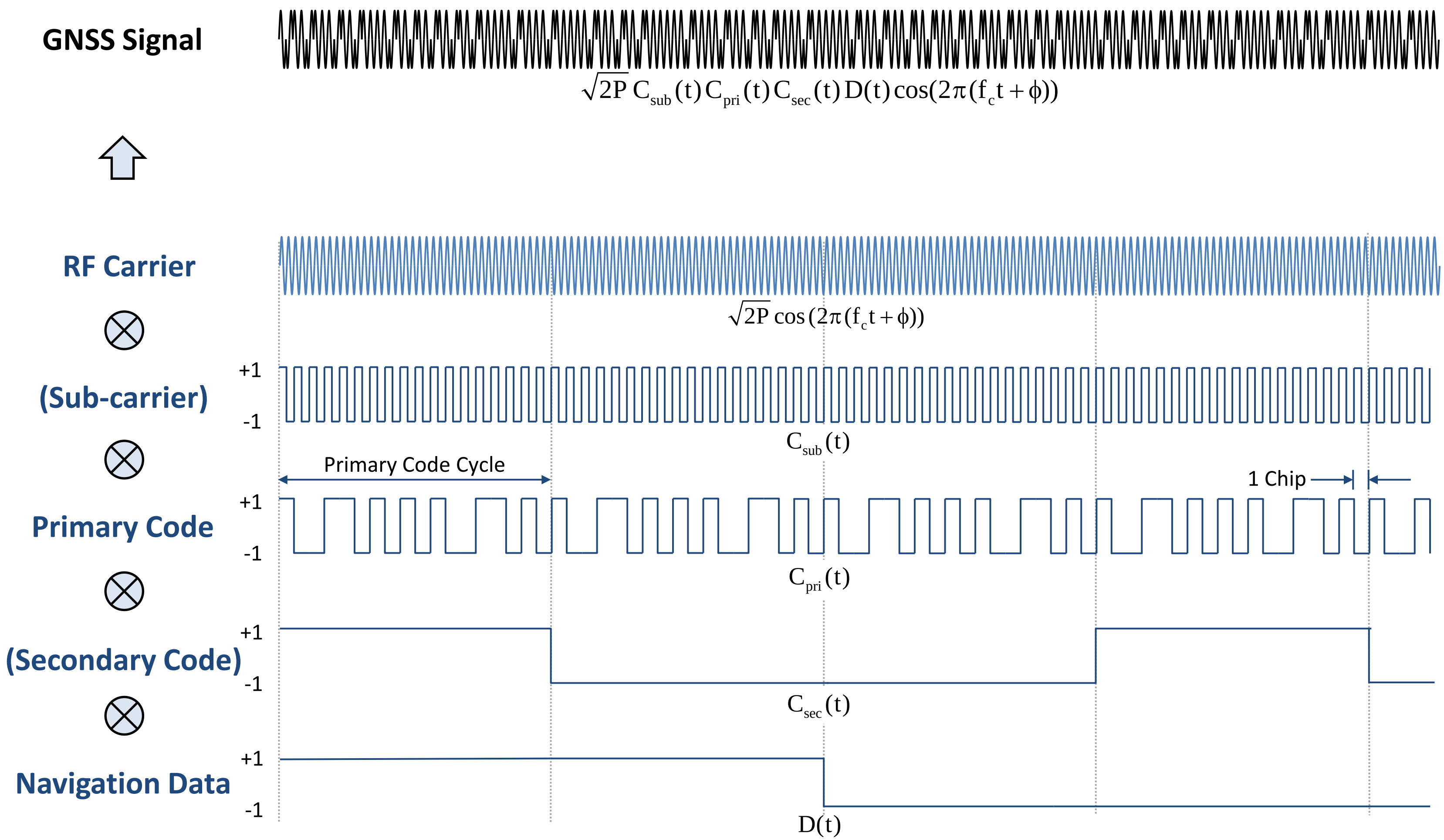
https://github.com/tomojitakasu/PocketSDR/doc/command_ref.pdf



https://github.com/tomojitakasu/PocketSDR/doc/pocket_sdr_help.pdf

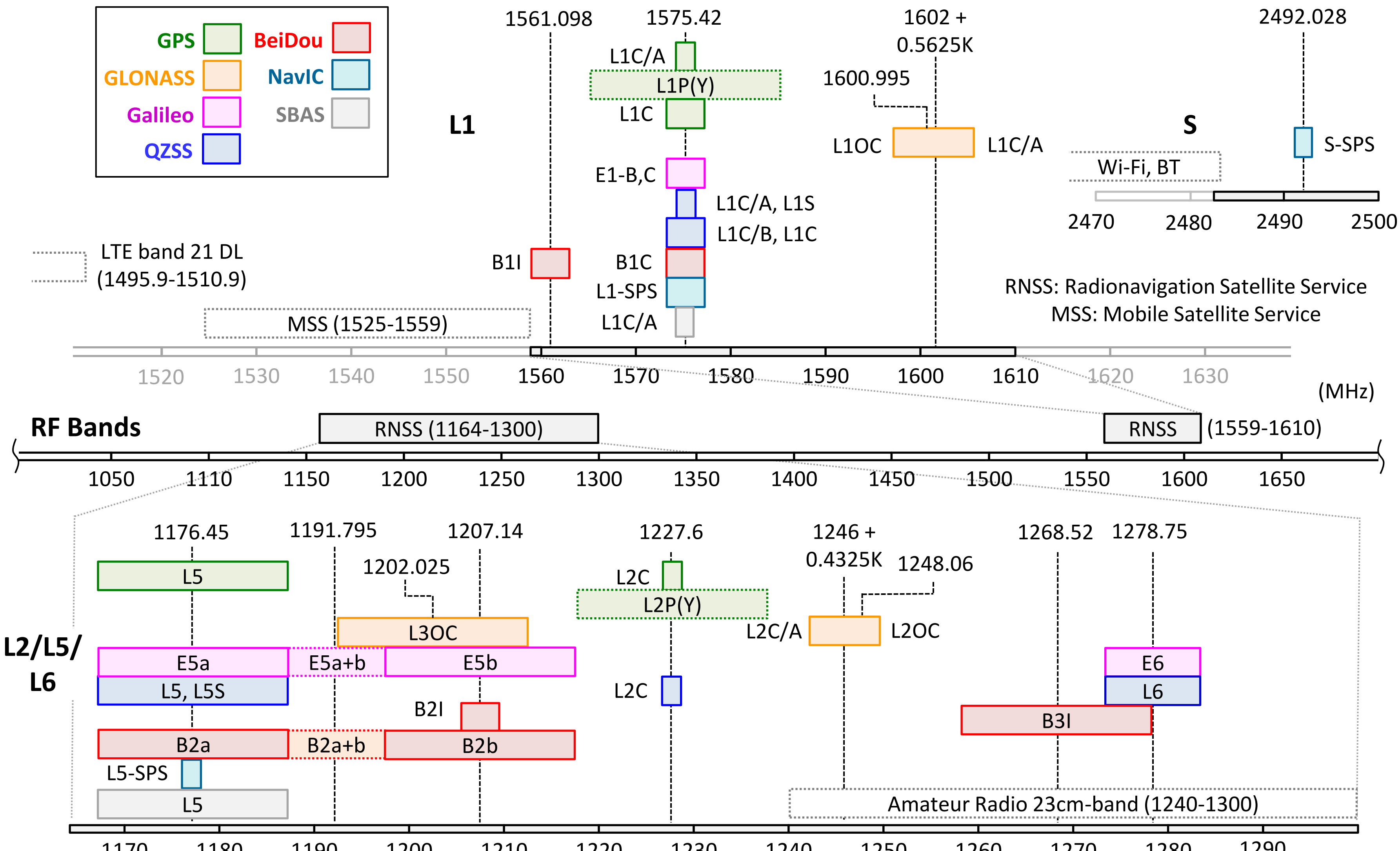
Modernized GNSS Signals

GNSS Signal Structure



f_c: Carrier Frequency (Hz), ϕ: Initial Phase (cycle)

GNSS Signal Bands



GNSS Signals (1/3)

Military or Restricted Signal

System	Carrier Freq. (MHz)	Signal	I/Q	Min Rec. Power (dBW)	Modulation	Primary Code Length (chip)	Primary Code Chip Rate (Mcps)	Primary Code Cycle (ms)	Secondary Code Length (chip)	Secondary Code Cycle (ms)	Navigation Data Data	Navigation Data Symbol Rate (sps)	Navigation Data Data Rate (bps)	Navigation Data FEC	Notes	Pocket SDR Signal ID
GPS [1][2][3]	1575.42	L1C/A	Q	-158.5	BPSK(1)	1023	1.023	1	-	-	LNAV	50	50	-		L1CA
		L1P(Y)*1	I	-161.5	BPSK(10)	1week	10.23	1week	-	-	LNAV	50	50	-		-
		L1M	I	?	BOC(10,5)	?	5.115	?	?	?	?	?	?	?	Block IIR-M~	-
		L1C-D	I	-163.0	BOC(1,1)	10230	1.023	10	-	-	CNAV-2	100	50	BCH,LDPC	GPS III~	L1CD
		L1C-P	I	-158.25	TMBOC(6,1,4/33)	10230	1.023	10	1800	18000	-	-	-	-		L1CP
	1227.6	L2C/A	Q	-164.5	BPSK(1)	1023	1.023	1	-	-	LNAV	50	50	-	Block IIR-M~	-
		L2P(Y)*1	I	-164.5/-161.5	BPSK(10)	1week	10.23	1week	-	1week	LNAV	50	50	-		-
		L2M	I	?	BOC(10,5)	?	5.115	?	?	?	?	?	?	?	Block IIR-M~	-
		L2C-M	Q/I	-160.0/ -158.5	BPSK(1)+TDM	10230	0.5115	20	-	-	LNAV	50	50	-	Block IIR-M~	-
											CNAV	50	25	1/2 *6		L2CM
		L2C-L			BPSK(1)+TDM	767250	0.5115	1500	-	-	-	-	-	-		(L2CL)
	1176.45	L5-I	I	-157.9/-157.0	BPSK(10)	10230	10.23	1	10 (NH)	10	CNAV	100	50	1/2 *6	Block IIF~	L5I
		L5-Q	Q	-157.9/-157.0	BPSK(10)	10230	10.23	1	20 (NH)	20	-	-	-	-		L5Q
GLONASS [4][5][6][7]	1602.0 + 0.5625K*2	L1C/A*4	I	-161.0	BPSK(0.5)	511	0.511	1	- / 2*3	- / 2*3	GLO-STR	100	50	-		G1CA
		L1P	Q	?	BPSK(5)	5110000	5.11	1000	-	-	?	?	?	-		-
	1600.995	L1OCd	Q	?	BPSK(1)+TDM	1023	0.5115	2	2 (MC)	4	GLO-STR	250	125	1/2 *6	GLO-K2~	G1OCD
		L1OCp			BOC(1,1)+TDM	4092	0.5115	8	-	-	-	-	-	-		G1OCP
		L1SC	I	?	?	?	?	?	?	?	?	?	?	?		-
	1246.0 + 0.4375K*2	L2C/A*5	I	-167.0	BPSK(0.5)	511	0.511	1	- / 2*3	- / 2*3	GLO-STR	100	50	-		G2CA
		L2P	Q	?	BPSK(5)	5110000	5.11	1000	-	-	?	?	?	-		-
	1248.06	L2CSI	Q	?	BPSK(1)+TDM	?	0.5115	?	?	?	?	?	?	?	GLO-K2~	-
		L2OCp	Q	?	BOC(1,1)+TDM	10230	0.5115	20	50	1000	-	-	-	-		G2OCP
		L2SC	I	?	?	?	?	?	?	?	?	?	?	?		-
	1202.025	L3OCd	I	?	BPSK(10)	10230	10.23	1	5 (BC)	5	GLO-STR	200	100	1/2 *6	GLO-K1~	G3OCD
		L3OCp	Q	?	BPSK(10)	10230	10.23	1	10 (NH)	10	-	-	-	-		G3OCP
Galileo[8]	1575.42	E1-A	Q	?	BOC(15,2.5)	?	2.5575	?	?	?	G/NAV	?	?	?	PRS	-
		E1-B	I	-157.0	CBOC(6,1,1/11)	4092	1.023	4	-	-	I/NAV	250	125	1/2 *6	OS, SoL, CS	E1B
		E1-C	-I		CBOC(6,1,1/11)	4092	1.023	4	25	100	-	-	-	-		E1C
	1176.45	E5a-I	I	-155.0	BPSK(10)	10230	10.23	1	20	20	F/NAV	50	25	1/2 *6	OS, CS	E5AI
		E5a-Q	Q		BPSK(10)	10230	10.23	1	100	100	-	-	-	-		E5AQ
	1207.14	E5b-I	I	-155.0	BPSK(10)	10230	10.23	1	4	4	I/NAV	250	125	1/2 *6	OS, SoL, CS	E5BI
		E5b-Q	Q		BPSK(10)	10230	10.23	1	100	100	-	-	-	-		E5BQ

*1 AS ON, *2 K = {-7, ..., +6}, *3 Odd FCN, *4 L1OF, *5 L2OF, *6 Convolutional Code (R=1/2, K=7), NH: Neuman Hoffman Code, MC: Manchester Code, BC: Barker Code

GNSS Signals (2/3)

Military or Restricted Signal

System	Carrier Freq. (MHz)	Signal	I/Q	Min Rec. Power (dBW)	Modulation	Primary Code			Secondary Code		Navigation Data				Notes	Pocket SDR Signal ID
						Length (chip)	Chip Rate (Mcps)	Cycle (ms)	Length (chip)	Cycle (ms)	Data	Symbol Rate (sps)	Data Rate (bps)	FEC		
Galileo (Cont.)	1191.795	E5a+b*7	-	(-152.0)	8-PSK(10)	10230	10.23	1	100	100	-	-	-	-		-
	1278.75	E6-A	Q	?	BOC(10,5)	?	5.115	?	?	?	G/NAV	?	?	?	PRS	-
		E6-B	I	-155.0	BPSK(5)	5115	5.115	1	-	-	C/NAV	1000	500	1/2 *6	CAS, HAS	E6B
		E6-C	-I		BPSK(5)	5115	5.115	1	100	100	-	-	-	-		E6C
QZSS [9][10][11][12]	1575.42	L1C/A	Q	-158.5*8	BPSK(1)	1023	1.023	1	-	-	LNAV	50	50	-		L1CA
		L1C/B	Q	-158.5	BOC(1,1)	1023	1.023	1	-	-	LNAV	50	50	-		L1CB
		L1C-D	I	-163.0*9	BOC(1,1)	10230	1.023	10	-	-	CNAV2	100	50	BCH,LDPC		L1CD
		L1C-P	Q	-158.25	BOC(1,1)	10230	1.023	10	1800	18000	-	-	-	-	Block I	L1CP
			I	-158.25*10	TMBOC(6,1,4/33)	10230	1.023	10	1800	18000	-	-	-	-	Block II ~	L1CP
		L1S	I	-161.0/-158.5	BPSK(1)	1023	1.023	1	-	-	L1S	500	250	1/2 *6	SLAS	L1S
	1227.6	L2C-M	I	-160.0/	BPSK(1)+TDM	10230	0.5115	20	-	-	CNAV	50	25	1/2 *6		L2CM
		L2C-L		-158.5	BPSK(1)+TDM	767250	0.5115	1500	-	-	-	-	-	-		(L2CL)
	1176.45	L5-I	I	-157.9/-157.0	BPSK(10)	10230	10.23	1	10 (NH)	10	CNAV	100	50	1/2 *6		L5I
		L5-Q	Q	-157.9/-157.0	BPSK(10)	10230	10.23	1	20 (NH)	20	-	-	-	-		L5Q
		L5S-I	I	-157.0*11	BPSK(10)	10230	10.23	1	-	-	L5S	500	250	1/2 *6	Normal mode	L5SI
									2 (MC)	2	L5S	500	250	1/2 *6	Verif. mode	L5SIV
		L5S-Q	Q		BPSK(10)	10230	10.23	1	20 (NH)	20	-	-	-	-	Normal mode	L5SQ
									2 (MC)	2	-	-	-	-	Verif. mode	L5SQV
	1278.75	L6D	I	-155.7	BPSK(5)+TDM*12	10230	2.5575	4	-	-	L6D	2000	2000	RS	CLAS	L6D
		L6L			BPSK(5)+TDM	1048575	2.5575	410	2 (MC)	820	-	-	-	-	Block I	-
		L6E			BPSK(5)+TDM*12	10230	2.5575	4	-	-	L6E	2000	2000	RS	MADOCA-PPP	L6E
BeiDou [13][14][15][16][17]	1561.098	B1I	I	-163.0	BPSK(2)	2046	2.046	1	20 (NH)	20	D1	50	50	BCH		B1I
								1	-	-	D2	500	500	BCH	GEO	B1I
		B1Q	Q	?	BPSK(2)	?	2.046	?	?	?	?	?	?	?		-
	1575.42	B1C-D	I	-159.0/	BOC(1,1)	10230	1.023	10	-	-	B-CNAV1	100	50	NB-LDPC	BDS-3	B1CD
		B1C-P	I+Q	-161.0	QMBOC(6,1,4/33)	10230	1.023	10	1800	18000	-	-	-	-		B1CP
		B1A-D	Q	?	BOC(14,2)	?	2.046	?	?	?	?	?	?	?		-
		B1A-P	Q			?	2.046	?	?	?	-	-	-	-		-
	1176.45	B2a-D	I	-156.0/	BPSK(10)	10230	10.23	1	5	5	B-CNAV2	200	100	NB-LDPC	BDS-3	B2AD
		B2a-P	Q	-158.0	BPSK(10)	10230	10.23	1	100	100	-	-	-	-		B2AP
	1207.14	B2I	I	?	BPSK(2)	2046	2.046	1	20 (NH)	20	D1	50	50	BCH		B2I
								1	-	-	D2	500	500	BCH	GEO	B2I

*7 AltBOC, *8 -164.0 dBW (SVID=7), *9 -167.2 dBW (SVID=7), *10 -162.4 dBW (SVID=7), *11 -162.6 dBW (SVID=3), *12 +CSK by Nav Data

GNSS Signals (3/3)

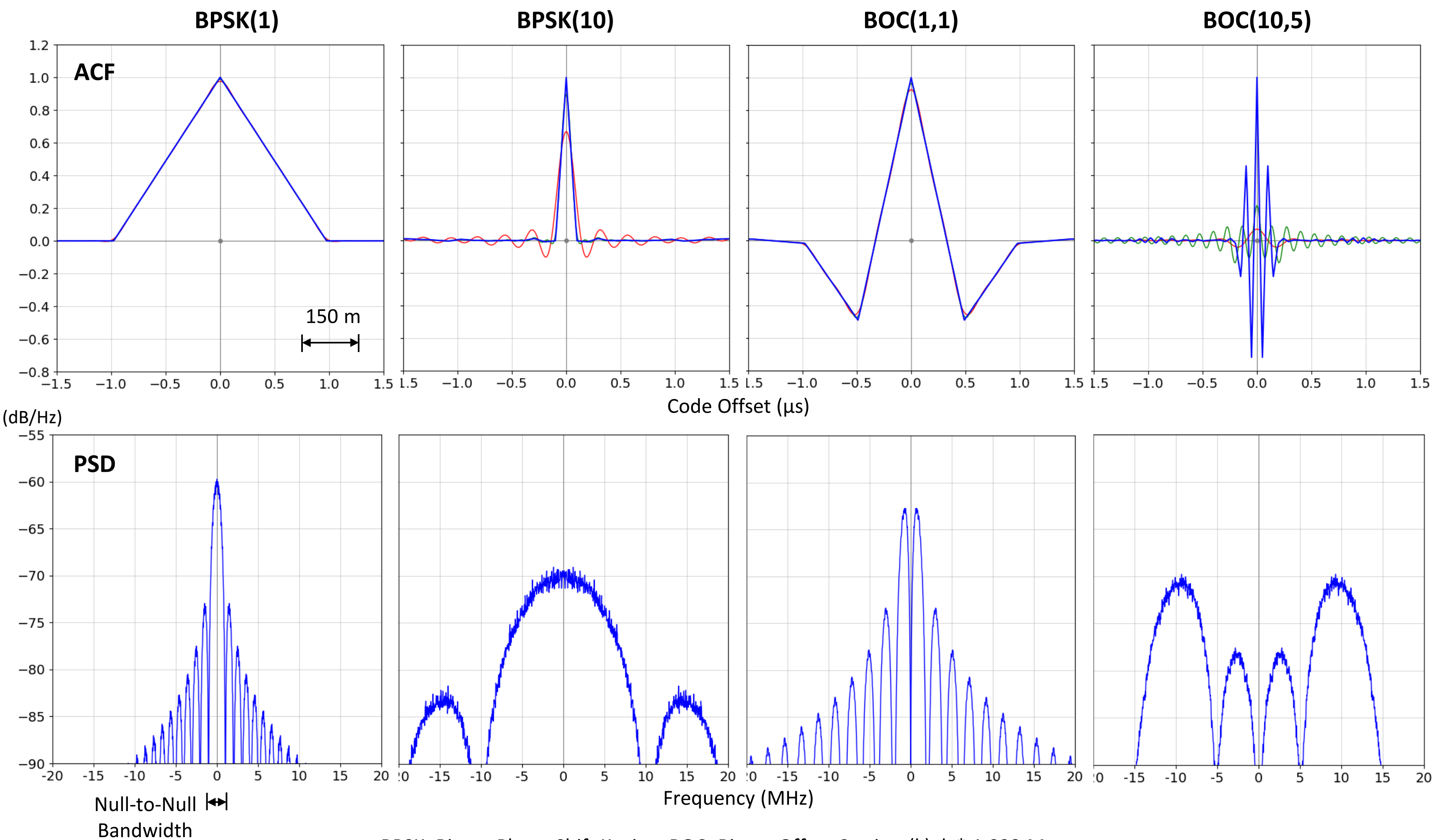
Military or Restricted Signal

System	Carrier Freq. (MHz)	Signal	I/Q	Min Rec. Power (dBW)	Modulation	Primary Code Length (chip)	Primary Code Chip Rate (Mcps)	Primary Code Cycle (ms)	Secondary Code Length (chip)	Secondary Code Cycle (ms)	Navigation Data Data	Navigation Data Symbol Rate (sps)	Navigation Data Data Rate (bps)	Navigation Data FEC	Notes	Pocket SDR Signal ID
BeiDou (Cont.)	1207.14	B2Q	Q	?	BPSK(10)	10230	10.23	1	?	?	?	?	?	?		-
		B2b-I	I	-160.0/ -162.0	BPSK(10)	10230	10.23	1	-	-	B-CNAV3	1000	500	NB-LDPC	BDS-3	B2BI
											B2b-PPP	1000	500	NB-LDPC	BDS-3, GEO	B2BI
		B2b-Q	Q	?	BPSK(10)	10230	10.23	1	?	?	?	?	?	?	BDS-3	-
	1191.795	B2a+b*13	-	?	8-PSK(10)	10230	10.23	1	?	?	-	-	-	-		-
	1268.52	B3I	I	-163.0	BPSK(10)	10230	10.23	1	20 (NH)	20	D1	50	50	BCH		B3I
								1	-	-	D2	500	500	BCH	GEO	B3I
		B3Q	Q	?	BPSK(10)	?	10.23	?	?	?	?	?	?	?		-
		B3A-D	I	?	BPSK(10)	?	10.23	?	?	?	?	?	?	?	BDS-3	-
		B3A-P	I		BPSK(10)	?	10.23	?	?	?	-	-	-	-		-
NavIC [18][19]	1575.42	L1-SPS-D	Q	-159.6	SBOC(6,1,1/11)	10230	1.023	10	-	-	IRN-NAV	100	50	BCH,LDPC	NVS-01~	I1SD
		L1-SPS-P	I	-158.2		10230	1.023	10	1800	18000	-	-	-	-		I1SP
	1176.45	L5-SPS	*14	-159.0	BPSK(1)	1023	1.023	1	-	-	IRN-NAV	50	25	1/2 *6		I5S
		L5-RS-D	*14	?	BOC(5,2)	?	2.046	?	?	?	?	50	25	1/2 *6		-
		L5-RS-P	*14	?	BOC(5,2)	?	2.046	?	?	?	-	-	-	-		-
	2492.028	S-SPS	*14	-162.3	BPSK(1)	1023	1.023	1	-	-	IRN-NAV	50	25	1/2 *6		(ISS)
		S-RS-D	*14	?	BOC(5,2)	?	2.046	?	?	?	?	50	25	1/2 *6		-
		S-RS-P	*14	?	BOC(5,2)	?	2.046	?	?	?	-	-	-	-		-
SBAS *15 [20]	1575.42	L1C/A	I	-	BPSK(1)	1023	1.023	1	-	-	SBAS	500	250	1/2 *6		L1CA
	1176.45	L5-I	I	-	BPSK(10)	10230	10.23	1	2 (MC)	2	L5 SBAS	500	250	1/2 *6	PRN120-158	L5I
		L5-Q	Q	-	BPSK(10)	10230	10.23	1	2 (MC)	2	-	-	-	-		L5Q

*13 ACE-BOC, *14 Interplex Modulation, *15 including QZSS L1Sb, BeiDou BDSBAS-B1C/B2a

[1] IS-GPS-200K, Navstar GPS space segment/navigation user interfaces - interface specification, 2019, [2] IS-GPS-800F, Navstar GPS space segment/user segment L1C interface - interface specification, 2019, [3] IS-GPS-705A, Navstar GPS space segment/user segment L5 interface - interface specification, 2010, [4] GLONASS interface control document - navigation radiosignal in bands L1, L2, version 5.1, 2008, [5] GLONASS interface control document - code division multiple access open service navigation signal in L1 frequency band, edition 1.0, 2016, [6] GLONASS interface control document - code division multiple access open service navigation signal in L2 frequency band, edition 1.0, 2016, [7] GLONASS interface control document - code division multiple access open service navigation signal in L3 frequency band, edition 1.0, 2016, [8] European GNSS (Galileo) open service signal-in-space interface control document (OS SIS ICD), Issue 1, Revision 3, 2016, [9] Quasi-Zenith satellite system interface specification - satellite positioning, navigation and timing service (IS-QZSS-PNT-003), 2018, [10] Quasi-zenith satellite system interface specification - sub-meter level augmentation service (IS-QZSS-L1S-003), 2018, [11] Quasi-zenith satellite system interface specification - centimeter level augmentation service (IS-QZSS-L6-003), 2018, [12] Quasi-zenith satellite system interface specification - positioning technology verification service (IS-QZSS-TV-004), 2023, [13] BeiDou navigation satellite system signal in space interface control document - open service signal B1I, version 3, 2019, [14] BeiDou navigation satellite system signal in space interface control document - open service signal B1C, version 1.0, 2017, [15] BeiDou navigation satellite system signal in space interface control document - open service signal B2a, version 1.0, 2017, [16] BeiDou navigation satellite system signal in space interface control document - open service signal B3I, version 1.0, 2018, [17] BeiDou navigation satellite system signal in space interface control document - Precise Point Positioning service signal PPP-B2b, version 1.0, 2020, [18] Indian Regional Navigation Satellite System, Signal in space ICD for standard positioning service version 1.1, 2017, [19] NAVIC signal in space ICD for standard positioning service in L1 frequency version 1.0, 2023, [20] RTCA, Minimum Operational Performance Standards for Airborne Equipment Using Global. Positioning System/Wide Area Augmentation System, DO-229, 1996

Modulation

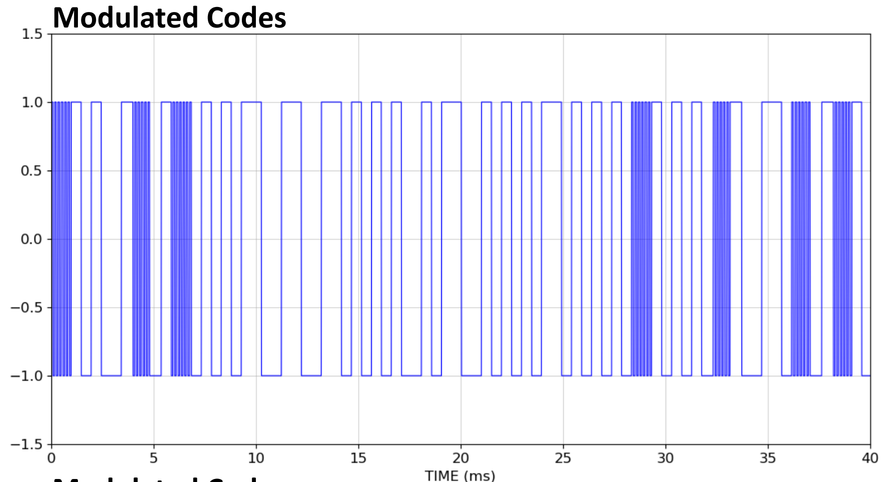


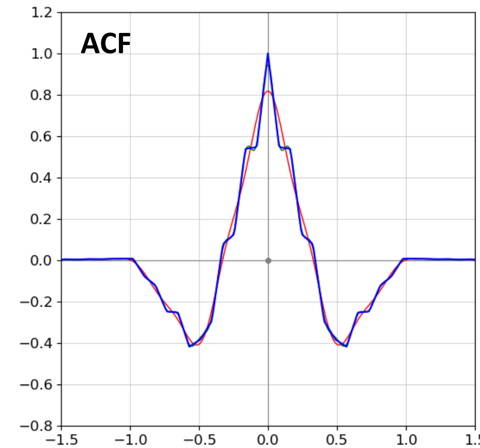
BPSK: Binary Phase-Shift Keying, BOC: Binary Offset Carrier, (k): k * 1.023 Mcps

ACF: Auto Correlation Function, PSD: Power Spectral Density, ACF with 4 MHz LPF, ACF with 8 MHz LPF

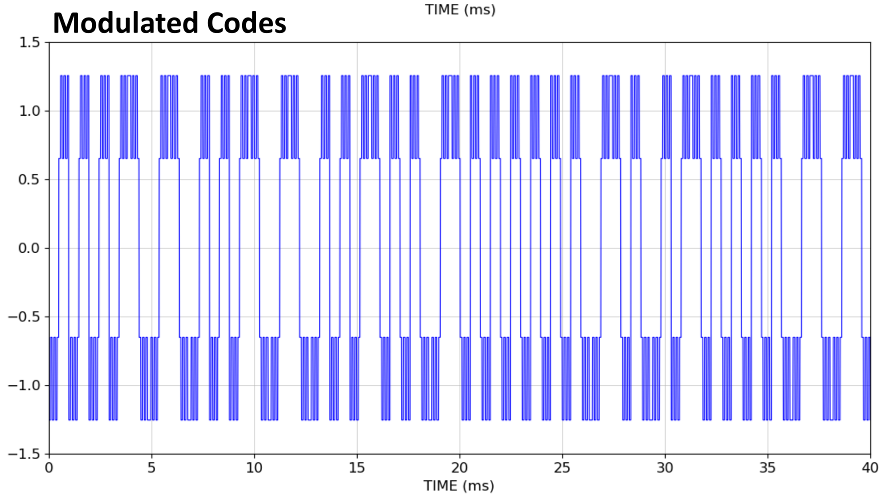
MBOC

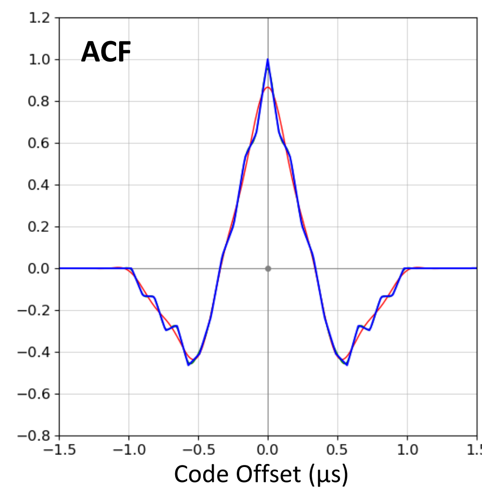
GPS/QZSS L1C-P: TMBOC (6,1,4/33)





Galileo E1B/C: CBOC (6,1,1/11)





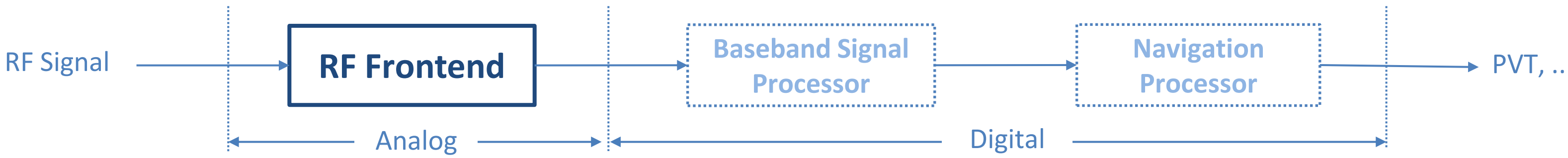
10 * log(10/11) = - 0.41 dB

BDS B1C-P -> QMBOC(6,1,4/33), NavIC L1-SPS -> SBOC(6,1,1/11), Galileo E5 -> AltBOC(15,10)

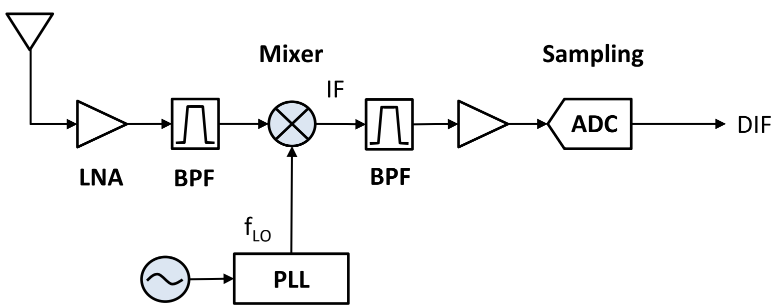
MBOC: Multiplexed BOC, TMBOC: Time-multiplexed BOC, CBOC: Composite BOC, QMBOC: Quadrature-multiplexed BOC, SBOC: Synthesized BOC

RF Frontend

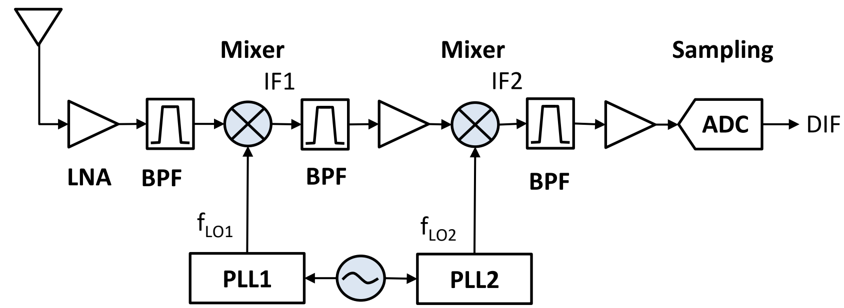
RF Frontend



Superheterodyne

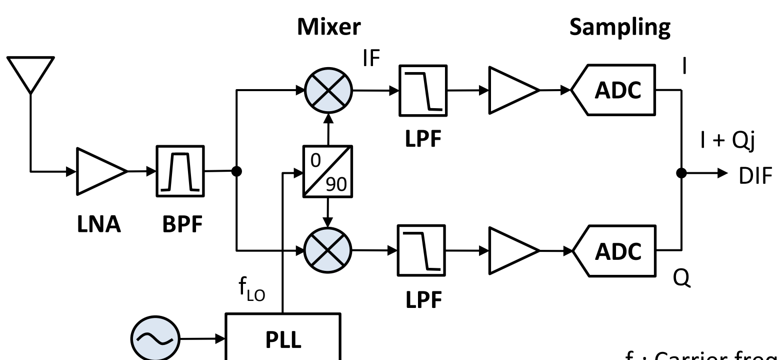


(Single Conversion)

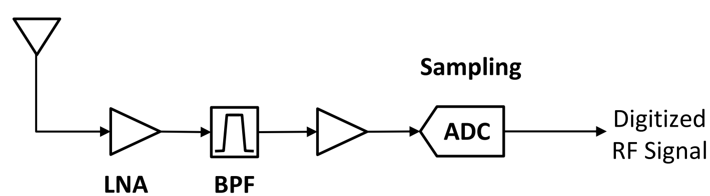


(Dual Conversion)

Direct Conversion (Zero-IF)



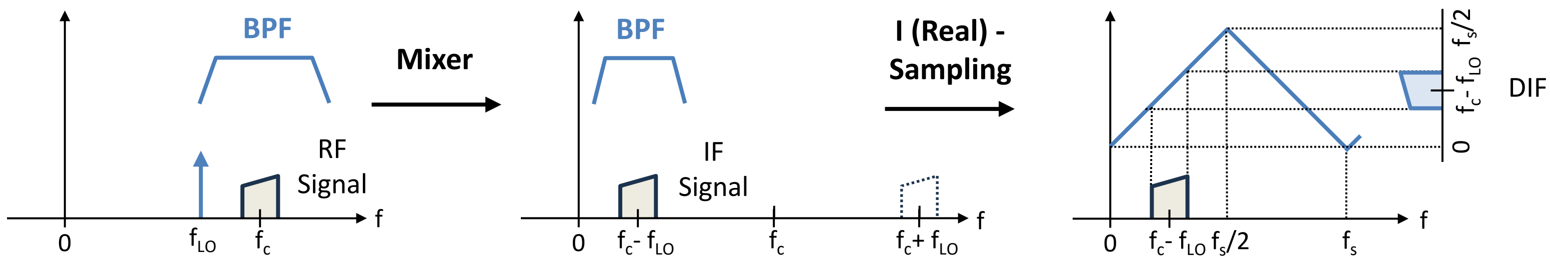
Direct (RF) Sampling



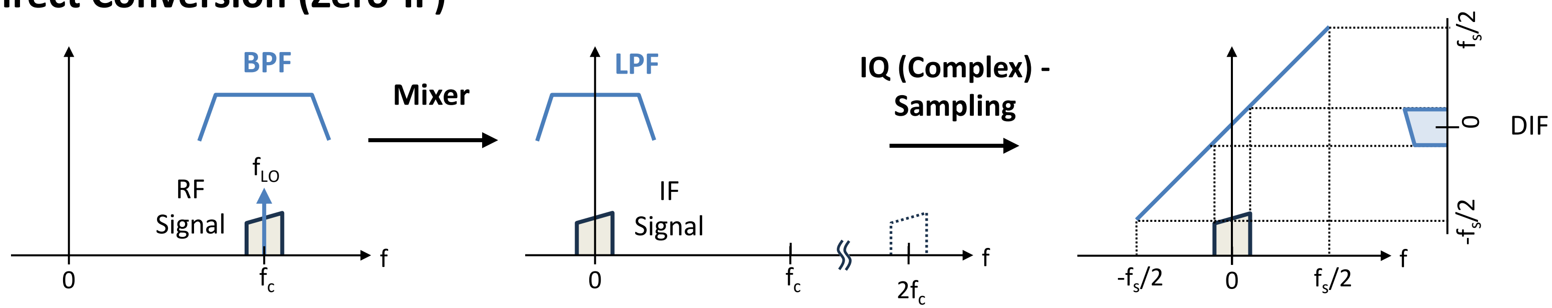
f_c: Carrier freq. (Hz), f_{LO}: Local oscillator freq. (Hz), DIF: Digitized IF signal

Down Conversion and Sampling

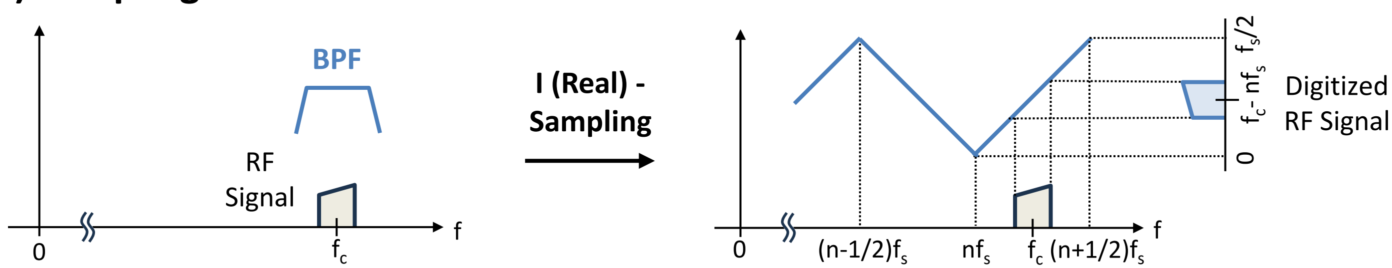
Superheterodyne



Direct Conversion (Zero-IF)



Direct (RF) Sampling



f_c: Carrier freq. (Hz),), f_{LO}: Local oscillator freq. (Hz), f_s: Sampling (ADC) freq. (Hz)

RF Frontends

RF-frontend	Vendor	# of CH		# of PLL		RF Bands	Sampling Type/Rate	RF LSI	FPGA	Host I/F	Price
		RX	TX	RX	TX						
USRP B210 [1]	Ettus Research, NI	2	2	1	1	70 MHz ~ 6 GHz	IQ, 12 bits ≤ 61.44 Msps	ADI AD9361	Spartan 6 XC6SLX150	USB 3.0	$2,165
SiGe GN3S Sampler [2]	GNSS Lab Univ Colorado	1	-	1	-	GPS L1	I or IQ, 2 bits ≤ 16.368 Msps	SiGe 4120	-	USB 2.0	$496
Stereo [3]	NSL	2	-	2	-	GNSS L1/L2/L5/L6	I+IQ, 2/3 bits 26 Msps	MAX2769B + MAX2112 + ...	Spartan-6	USB 2.0	$800
RTL-SDR [4]	RTLSDR.com	1	-	1	-	500 kHz ~ 1.75 GHz	IQ, 8 bits ≤ 2.56 Msps	R820T + RTL2832U	-	USB 2.0	$20 - $50
Blade RF [5]	NuBand	2	2	1	1	300 MHz ~ 3.8 GHz	IQ, 12 bits ≤ 40 Msps	Lime Micro. LMS6002D	Cyclone IV E	USB 3.0	$520
Lime SDR [6]	Lime Microsystems	2	2	1	1	100 kHz ~ 3.8 GHz	IQ, 12 bits ≤ 61.44 Msps	Lime Micro. LMS7002M	Cyclone IV EP4CE40F23	USB 3.0	$299
NUT4NT [7]	Amungo Navigation	4	-	2	-	GNSS L1/L2/L5/L6	I, 2 bits ≤ 99 Msps	NTLab NT1065	Lattice ECP5	USB 3.0	$399
Pluto SDR [8]	Analog Devices (ADI)	1	1	1	1	325 kHz ~ 3.8 GHz	IQ, 12 bits ≤ 61.44 Msps	ADI AD9363	Zynq Z-7010	USB 2.0	$233
Pocket SDR FE 2/4/8CH	-	2/4/8	-	2/4/8	-	GNSS L1/L2/L5/L6	I or IQ, 2/3 bits ≤ 32/48 Msps	MAX2771 x 2/4/8	-	USB 2.0/3.0	$60/$130/ $200 *

* Parts only


USRP B210


GN3S Sampler


Stereo


Blade RF


Lime SDR


RTL-SDR


NUT4NT

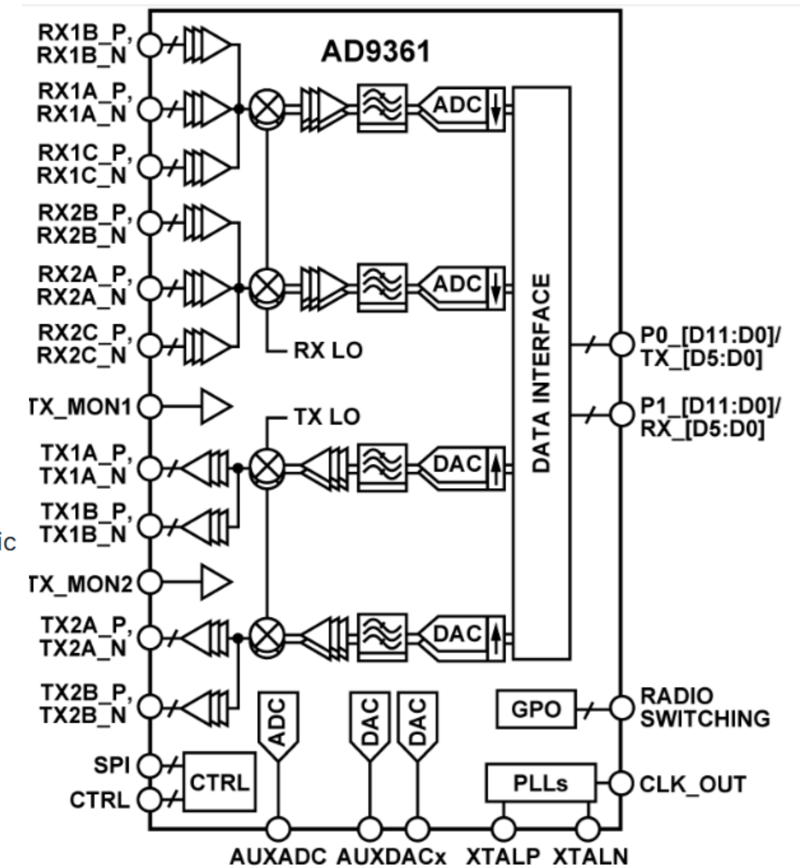

Pluto SDR

[1] https://www.ettus.com/all-products/ub210-kit/, [2] https://ccar.colorado.edu/gnss/, [3] https://gmvnsl.com/advanced-gnns-hw-sw/,
[4] https://rtl-sdr.com/, [5] https://www.nuand.com/bladerf-1/, [6] https://limemicro.com/products/boards/limesdr/, [7] https://www.amungo-navigation.com/,
[8] https://www.analog.com/en/resources/evaluation-hardware-and-software/evaluation-boards-kits/adalm-pluto.html

AD9361

RF Agile Transceiver

- RF 2 × 2 transceiver with integrated 12-bit DACs and ADCs
- TX band: 47 MHz to 6.0 GHz
- RX band: 70 MHz to 6.0 GHz
- Supports TDD and FDD operation
- Tunable channel bandwidth: <200 kHz to 56 MHz
- Dual receivers: 6 differential
- Superior receiver sensitivity with a noise figure of 2 dB at 800 MHz LO
- RX gain control
- Real-time monitor and control signals for manual gain
- Independent automatic gain control
- Dual transmitters: 4 differential outputs
- Highly linear broadband transmitter
  - TX EVM: ≤−40 dB
  - TX noise: ≤−157 dBm/Hz noise floor
  - TX monitor: ≥66 dB dynamic range with 1 dB accuracy
- Integrated fractional-N synthesizers
- 2.4 Hz maximum local oscillator (LO) step size
- Multichip synchronization
- CMOS/LVDS digital interface



Block Diagram

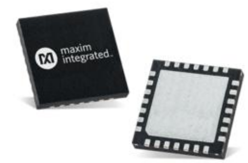
https://www.analog.com/en/products/ad9361.html

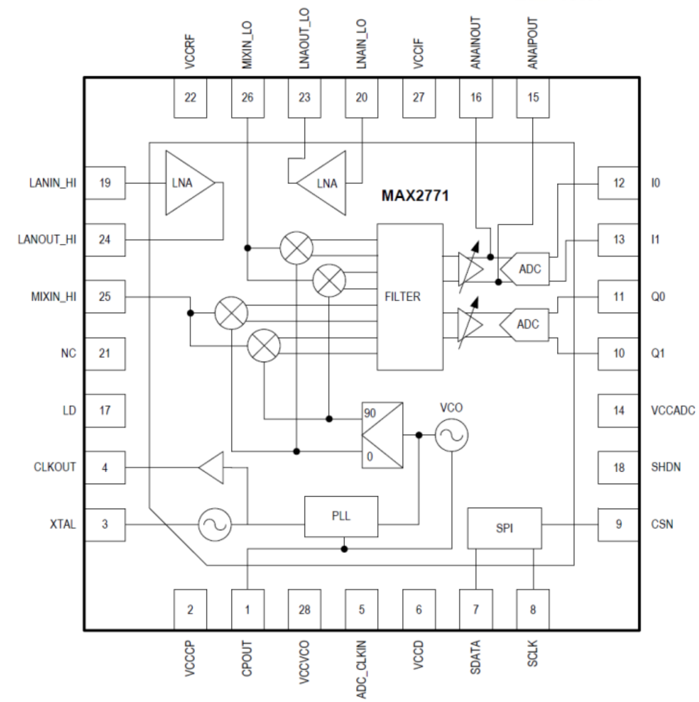
MAX2771 (1/5)

Multiband Universal GNSS Receiver

- Multi-Constellation Support: GPS, Galileo, GLONASS, BeiDou, IRNSS, QZSS, SBAS
- Multiband Support: L1, L2, L5, E1, E5, E6, B1, B2, B3
- Programmable IF Bandwidths of 2.5MHz, 4.2MHz, 8.7MHz, 16.4MHz, 23.4MHz, 36MHz: Supports Wide-Band Carriers for Precision Applications (e.g., GPS L5, Galileo E5)
- Operates in Low IF or Zero IF Mode: Programmable IF Center Frequency
- Fractional-N Synthesizer with Integrated VCO Supports Wide Range of Reference Frequencies
- On-Chip LNAs to Support Multiple Bands
- 1.4dB Cascaded Noise Figure and 110dB of Cascaded Gain with Gain Control Range of 59dB from PGA
- Integrated Crystal Oscillator
- Supply Voltage Range: 2.7V to 3.3V
- 28-Pin, RoHS-Compliant, Thin QFN Lead-Free Package (5mm x 5mm)

maxim integrated





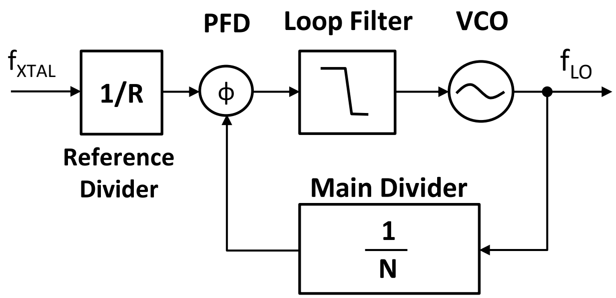
Block Diagram

ADI/maxim integrated, MAX2771 Multiband Universal GNSS Receiver Data Sheet, 2018

MAX2771 (2/5)

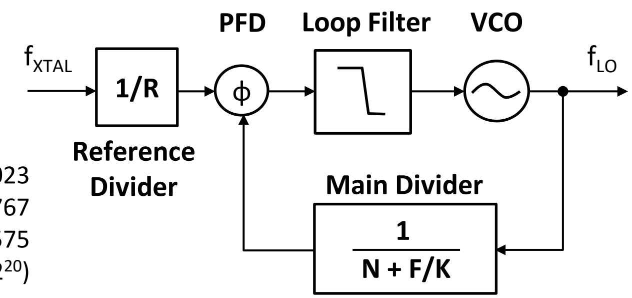
Frequency Synthesizer (PLL)

Integer-N PLL



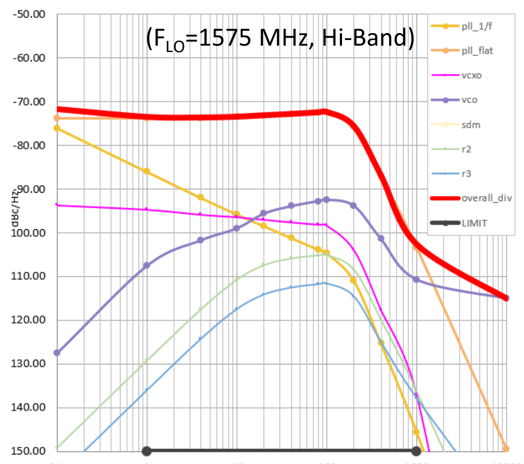
R = 1 ~ 1023
N = 36 ~ 32767
F = 0 ~ 1048575
K = 1048576 (2^{20})

Fractional-N PLL

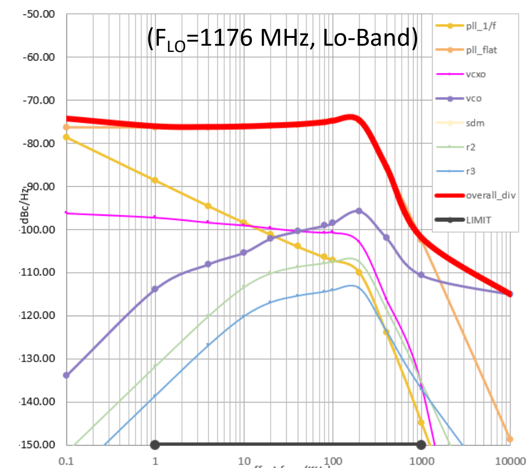


PFD: Phase Frequency Detector, VCO: Voltage Controlled Oscillator, f_{XTAL}: TCXO freq. (Hz), f_{LO}: Local Oscillator Freq. (Hz)

PLL Phase Noise (Simulated) (dBc/Hz)



f_{XTAL}=24 MHz, RDIV=8,
Loop Filter RC:
C1=15 pF, R2=15 KΩ,
C2=750 pF



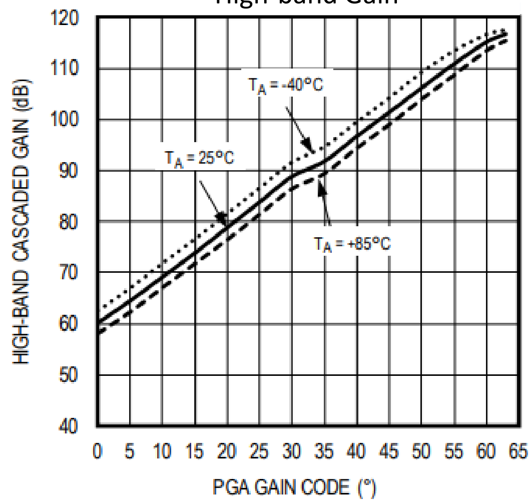
https://www.analog.com/media/en/designtools/calculators/max2771-pll-simulator.xlsx

maxim integrated, MAX2771 PLL Loop Filter Calculator User Guide, 2018

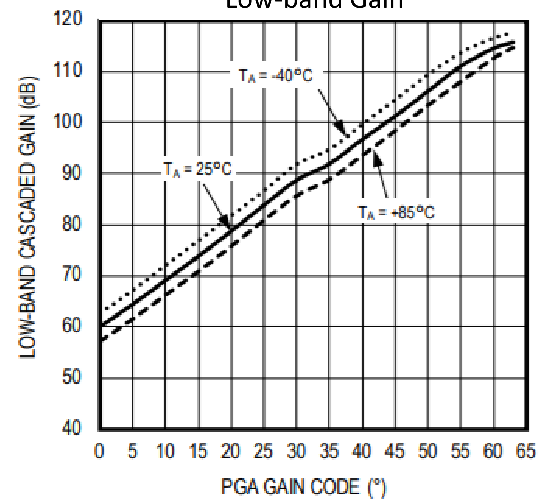
MAX2771 (3/5)

LNA

High-band Gain



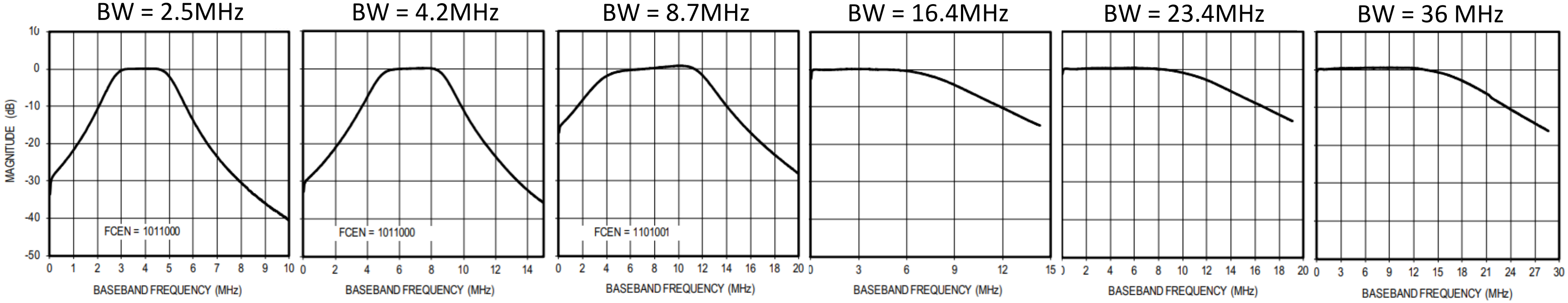
Low-band Gain



IF Filter

Filter Response (3rd-order Butterworth)

BW = 2.5MHz BW = 4.2MHz BW = 8.7MHz BW = 16.4MHz BW = 23.4MHz BW = 36 MHz

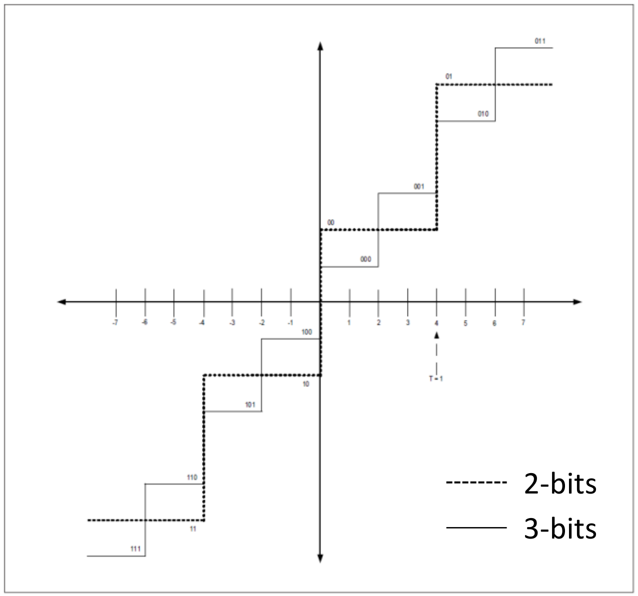


ADI/maxim integrated, MAX2771 Multiband Universal GNSS Receiver Data Sheet, 2018

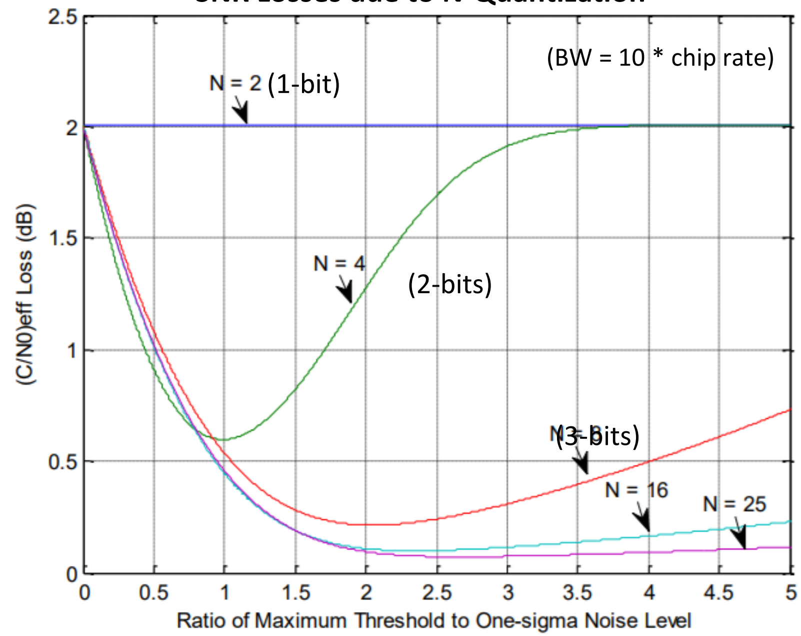
MAX2771 (4/5)

ADC

ADC Quantization Levels [1]

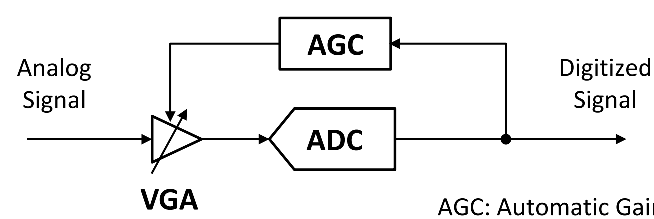


SNR Losses due to N-Quantization [2]



Output Data Format [1]

INTEGER VALUE	SIGN/MAGNITUDE			UNSIGNED BINARY			TWO'S COMPLEMENT BINARY		
	1b	2b	3b	1b	2b	3b	1b	2b	3b
7	0	01	011	1	11	111	0	01	011
5	0	01	010	1	11	110	0	01	010
3	0	00	001	1	10	101	0	00	001
1	0	00	000	1	10	110	0	00	000
-1	1	10	100	0	01	011	1	11	111
-3	1	10	101	0	01	010	1	11	110
-5	1	11	110	0	00	001	1	10	101
-7	1	11	111	0	00	000	1	10	100



AGC: Automatic Gain Control
VGA: Variable Gain Amplifier

[1] ADI/maxim integrated, MAX2771 Multiband Universal GNSS Receiver Data Sheet, 2018
[2] C.J.Hegarty, Analytical Model for GNSS Receiver Implementation Losses, Navigation, 2011

MAX2771 (5/5)

Configuration Register Settings

Register	Description	Register	Description
CHIPEN	Chip enable (0:disable, 1:enable)	**STRMSTOP**	Disable data streaming (rising edge)
IDLE	Idle enable (0:operating-mode, 1:idle-mode)	**STRMBITS**	Number of bits streamed (1:IMSB/ILSB, 3:IMSB/ILSB/QMSB/QLSB)
MIXPOLE	Mixer pole selection (0:13MHz, 1:36MHz)		
LNAMODE	LNA mode selection (0:high-band, 1:low-band, 2:disable)	**STAMPEN**	Enable insertion of frame numbers (0:disable, 1:enable)
MIXERMODE	Mixer mode selection (0:high-band, 1:low-band, 2:disable)	**TIMESYNCEN**	Enable output of time sync pulse when streaming enabled by STRMEN
FCEN	IF filter center frequency: (128-FCEN)/2*{0.195|0.66|0.355} MHz	**DATASYNCEN**	Enable sync pulse at DATASYNC
FBW	IF filter BW (0:2.5MHz, 1:8.7MHz, 2:4.2MHz, 3:23.4MHz, 4:36MHz, 7:16.4MHz)	**STRMRST**	Reset all counters
		LOBAND	Local oscillator band selection (0:L1, 1:L2/L5)
F3OR5	Filter order selection (0:5th, 1:3rd)	**REFOUTEN**	Output clock buffer enable (0:disable, 1:enable)
FCENX	Polyphase filter selection (0:lowpass, 1:bandpass)	**IXTAL**	Current programing for XTAL (1:normal, 3:high-current)
FGAIN	IF filter gain setting (0:-6dB, 1:normal)	**ICP**	Charge pump current selection (0:0.5mA, 1:1mA)
ANAIMON	Enable continuous spectrum monitoring (0:disable, 1:enable)	**INT_PLL**	PLL mode control (0:fractional-N, 1:integer-N)
IQEN	I and Q channel enable (0:I-CH-only, 1:I/Q-CH)	**PWRSAV**	Enable PLL power-save mode (0:disable, 1:enable)
GAINREF	AGC gain reference value (0-4095)	**NDIV**	PLL integer division ratio (36-32767): F_LO= F_XTAL/RDIV*(NDIV+FDIV/2^20)
SPI_SDIO_CONFIG	SPI SDIO pin config (0:none, 1:pull-down, 2:pull-up, 3:bus-hold)	**RDIV**	PLL reference division ratio (1-1023)
AGCMODE	AGC mode control (0:independent-I/Q, 2:gain-set-by-GAININ)	**FDIV**	PLL fractional division ratio (0-1048575)
FORMAT	Output data format (0:unsigned, 1:sign-magnitude, 2:2's-complement)	**EXTADCCLK**	External ADC clock selection (0:internal, 1:ADC_CLKIN)
		PREFRACDIV_SEL	Clock pre-divider selection (0:bypass, 1:enable)
BITS	Number of bits in ADC (0:1bit, 2:2bit, 4:3bit)	**REFCLK_L_CNT**	Clock pre-divider L counter value (0-4095): L_CNT/(4096-M_CNT+L_CNT)
DRVCFG	Output driver config (0:CMOS-logic, 2:analog)		
DIEID	Identifiers version of IC	**REFCLK_M_CNT**	Clock pre-divider M counter value (0-4095)
GAININ	PGA gain value programming in steps of approx 1dB per LSB (0-63)	**ADCCLK**	Integer clock div/mul selection (0:enable, 1:bypass)
		REFDIV	Integer clock div/mul ratio (0:x2, 1:1/4, 2:1/2, 3:x1, 4:x4)
HILODEN	Enable output driver to drive high loads (0:disable, 1:enable)	**FCLKIN**	ADC clock divider selection (0:bypass, 1:enable)
FHIPEN	Enable highpass coupling between filter and PGA (0:disable,1:enable)	**ADCCLK_L_CNT**	ADC clock divider L counter value (0-4095): L_CNT/(4096-M_CNT+L_CNT)
PGAIEN	I-CH PGA enable (0:disable, 1:enable)	**ADCCLK_M_CNT**	ADC clock divider M counter value (0-4095)
PGAQEN	Q-CH PGA enable (0:disable, 1:enable)	**CLKOUT_SEL**	CLKOUT selection (0:integer-clock-div/mul, 1:ADC-clock)
STRMEN	Enable DSP interface (0:disable, 1:enable)	**MODE**	DSP interface mode selection
STRMSTART	Enable data streaming (rising edge)		

[ADI/maxim integrated, MAX2771 Multiband Universal GNSS Receiver Data Sheet, 2018](#)

Example of MAX2771 Setting

$ pocket_conf PocketSDR/conf/pocket_L1L5_24MHz.conf; pocket_conf -a

```
#
#  Pocket SDR device settings (MAX2771)
#
#  [CH1] F_LO = 1575.420 MHz, F_ADC = 24.000 MHz (IQ), F_FILT =  0.0 MHz, BW_FILT =  4.2 MHz
#  [CH2] F_LO = 1176.450 MHz, F_ADC =  0.000 MHz (IQ), F_FILT =  0.0 MHz, BW_FILT = 16.4 MHz

[CH1]
CHIPEN          =       1  # Chip enable (0:disable,1:enable)
IDLE            =       0  # Idle enable (0:operating-mode,1:idle-mode)
MIXPOLE         =       0  # Mixer pole selection (0:13MHz,1:36MHz)
LNAMODE         =       0  # LNA mode selection (0:high-band,1:low-band,2:disable)
MIXERMODE       =       0  # Mixer mode selection (0:high-band,1:low-band,2:disable)
FCEN            =       0  # IF filter center frequency: (128-FCEN)/2*{0.195|0.66|0.355} MHz
FBW             =       2  # IF filter BW (0:2.5MHz,1:8.7MHz,2:4.2MHz,3:23.4MHz,4:36MHz,
                           # 7:16.4MHz)
F3OR5           =       1  # Filter order selection (0:5th,1:3rd)
FCENX           =       0  # Polyphase filter selection (0:lowpass,1:bandpass)
FGAIN           =       1  # IF filter gain setting (0:-6dB,1:normal)
ANAIMON         =       0  # Enable continuous spectrum monitoring (0:disable,1:enable)
IQEN            =       1  # I and Q channel enable (0:I-CH-only,1:I/Q-CH)
GAINREF         =     170  # AGC gain reference value (0-4095)
SPI_SDIO_CONFIG =       0  # SPI SDIO pin config (0:none,1:pull-down,2:pull-up,3:bus-hold)
AGCMODE         =       0  # AGC mode control (0:independent-I/Q,2:gain-set-by-GAININ)
FORMAT          =       1  # Output data format (0:unsigned,1:sign-magnitude,
                           # 2:2's-complement)
BITS            =       2  # Number of bits in ADC (0:1bit,2:2bit,4:3bit)
DRVCFG          =       0  # Output driver config (0:CMOS-logic,2:analog)
DIEID           =       0  # Identifiers version of IC
GAININ          =      58  # PGA gain value programming in steps of approx 1dB per LSB (0-63)
HILODEN         =       0  # Enable output driver to drive high loads (0:disable,1:enable)
FHIPEN          =       0  # Enable highpass coupling between filter and PGA
                           # (0:disable,1:enable)
PGAIEN          =       1  # I-CH PGA enable (0:disable,1:enable)
PGAQEN          =       1  # Q-CH PGA enable (0:disable,1:enable)
STRMEN          =       0  # Enable DSP interface (0:disable,1:enable)
STRMSTART       =       0  # Enable data streaming (rising edge)
STRMSTOP        =       0  # Disable data streaming (rising edge)
STRMBITS        =       1  # Number of bits streamed (1:IMSB/ILSB,3:IMSB/ILSB/QMSB/QLSB)
STAMPEN         =       0  # Enable insersion of frame numbers (0:disable,1:enable)
TIMESYNCEN      =       0  # Enable output of time sync pulse when streaming enabled by
                           # STRMEN
DATASYNCEN      =       0  # Enable sync pulse at DATASYNC
STRMRST         =       0  # Reset all counters
LOBAND          =       0  # Local oscillator band selection (0:L1,1:L2/L5)
REFOUTEN        =       1  # Output clock buffer enable (0:disable,1:enable)
IXTAL           =       1  # Current programing for XTAL (1:normal,3:high-current)
ICP             =       0  # Charge pump current selection (0:0.5mA,1:1mA)
INT_PLL         =       1  # PLL mode control (0:fractional-N,1:integer-N)
PWRSAV          =       0  # Enable PLL power-save mode (0:disable,1:enable)
NDIV            =   26257  # PLL integer division ratio (36-32767):
                           # F_LO=F_XTAL/RDIV*(NDIV+FDIV/2^20)
RDIV            =     400  # PLL reference division ratio (1-1023)
FDIV            =       0  # PLL fractional division ratio (0-1048575)
EXTADCCLK       =       0  # External ADC clock selection (0:internal,1:ADC_CLKIN)
PREFRACDIV_SEL  =       0  # Clock pre-divider selection (0:bypass,1:enable)
REFCLK_L_CNT    =       0  # Clock pre-divider L counter value (0-4095):
                           # L_CNT/(4096-M_CNT+L_CNT)
REFCLK_M_CNT    =       0  # Clock pre-divider M counter value (0-4095)
ADCCLK          =       0  # Integer clock div/mul selection (0:enable,1:bypass)
REFDIV          =       3  # Integer clock div/mul ratio (0:x2,1:1/4,2:1/2,3:x1,4:x4)
FCLKIN          =       0  # ADC clock divider selection (0:bypass,1:enable)
ADCCLK_L_CNT    =       0  # ADC clock divider L counter value (0-4095):
                           # L_CNT/(4096-M_CNT+L_CNT)
ADCCLK_M_CNT    =       0  # ADC clock divider M counter value (0-4095)
CLKOUT_SEL      =       1  # CLKOUT selection (0:integer-clock-div/mul,1:ADC-clock)
MODE            =       0  # DSP interface mode selection

[CH2]
CHIPEN          =       1  # Chip enable (0:disable,1:enable)
IDLE            =       0  # Idle enable (0:operating-mode,1:idle-mode)
MIXPOLE         =       0  # Mixer pole selection (0:13MHz,1:36MHz)
LNAMODE         =       1  # LNA mode selection (0:high-band,1:low-band,2:disable)
MIXERMODE       =       1  # Mixer mode selection (0:high-band,1:low-band,2:disable)
FCEN            =       0  # IF filter center frequency: (128-FCEN)/2*{0.195|0.66|0.355} MHz
FBW             =       7  # IF filter BW (0:2.5MHz,1:8.7MHz,2:4.2MHz,3:23.4MHz,4:36MHz,
                           # 7:16.4MHz)
F3OR5           =       1  # Filter order selection (0:5th,1:3rd)
...
```

Reference Oscillator

TCXO (Temperature Compensated Crystal Oscillator)

EPSON **TG2520SMN-24.0000M-MCGNNM3**

(1) (2) (3) (4)(5)(6) (7)

(1) Model (TG2016: 2.0 x 1.6 mm, TG2520: 2.5 x 2.0 mm)
(2) Output (S: Clipped sine wave)
(3) Frequency
(4) Supply voltage (E: 1.8V, M: 2.8 ~ 3.3V)
(5) Freq./temp. charac. (C: ±0.5 x 10^{-6}, F: ±2.0 x 10^{-6} MAX)
(6) Operating temperature: (G: -40 C ~ +85 C)
(7) VC function (N: non, B: 0.9V, C: 1.4V, D:1.5V, E: 1.65V)

Item	Symbol	VC-TCXO	TCXO	Conditions / Remarks
Output frequency range	f_0	10 MHz to 55MHz		
		16, 16.368, 16.369, 19.2, 20, 24, 25, 26, 27, 27.6, 30, 32, 38.4, 40, 48, 50, 52 MHz		Standard frequency
Supply voltage	Vcc	1.8 V ±0.1 V / 2.8 V ±5 % / 3.0 V ±5 % / 3.3 V ±5 %		Supply voltage range :1.7 V to 3.63 V
Storage temperature	T_stg	-40 °C to +90 °C		Storage as single product.
Operating temperature	T_use	G: -40 C to +85 C		
Frequency tolerance	f_tol	±1.5 × 10^{-6} Max.		After reflow, +25 C
Frequency/temperature characteristics	f_0-Tc	C: ±0.5 × 10^{-6} Max. / G: -40 C to +85 C F: ±2.0 × 10^{-6} Max. / G: -40 C to +85 C		Standard stability version
Frequency/load coefficient	f_0-Load	±0.1 × 10^{-6} Max.		10 kΩ // 10 pF ±10 %
Frequency/voltage coefficient	f_0-Vcc	±0.1 × 10^{-6} Max.		Vcc ± 5 %
Frequency aging	f_age	±0.5 × 10^{-6} Max.		+25 C, First year, 10MHz, 12 MHz≤ f_0 ≤20 MHz, 24 MHz≤ f_0 ≤40 MHz
		±1.5 × 10^{-6} Max.		+25 C ,First year, 10 MHz< f_0 <12 MHz, 20 MHz< f_0 <24 MHz, 40 MHz< f_0 ≤55 MHz
Current consumption	Icc	1.5 mA Max.		10 MHz≤ f_0 ≤26 MHz
		1.8 mA Max.		26 MHz< f_0 ≤40 MHz
		2.0 mA Max.		40 MHz< f_0 ≤50 MHz
		2.1 mA Max.		50 MHz< f_0 ≤55 MHz
Input resistance	Rin	500 kΩ Min.	-	Vc - GND (DC)
Frequency control range	f_cont	±8.0 × 10^{-6} to ±12.0 × 10^{-6}	-	B: Vc =0.9 V ±0.6 V (Vcc =1.8 V) or C: Vc =1.4 V ±1.0 V (Vcc =2.8 V) or D: Vc =1.5 V ±1.0 V (Vcc =3.0 V) or E: Vc =1.65 V ±1.0 V (Vcc =3.3 V)
Frequency change polarity	-	Positive polarity	-	
Symmetry	SYM	45 % to 55 %		GND level (DC cut)
Output voltage	VPP	0.8 V Min.		Peak to Peak
Start-up time	t_str	1.0 ms Max.		T=0 at 90% Vcc
Output load condition	Load_R	10 kΩ		DC cut capacitor = 0.01 µF
	Load_C	10 pF		

Seiko Epson, VC-TCXO/TCXO High Stability / Low Noise TG2016SMN/TG2520SMN Data Sheet

Pocket SDR FE

Device	FE 2CH	FE 4CH (ver.0.13 ~)	FE 8CH (ver.0.14 ~)	Notes
RF Input	SMA x 1	SMA x 1	SMA x 8	Antenna DC 4.2-5V, ≤ 100mA *1
# of RF CH	2 (CH1: L1, CH2: L2/L5/L6)	4 (CH1-4: L1 or L2/L5/L6)	8 (CH1-8: L1 or L2/L5/L6)	
LO Frequency	1525 - 1610 MHz (L1) or 1160 - 1290 MHz (L2/L5/L6)			
Sampling Type	I-sampling (2 or 3 bits) or IQ-sampling (2 bits)			
Sampling Rate	4, 6, 8, 12, 16, 24 or 32 Msps	4, 6, 8, 12, 16, 24, 32 or 48 Msps		
IF Filter	Bandpass or Lowpass, 3rd or 5th-order Butterworth, Bandwidth: 2.5, 4.2, 8.7, 16.4*, 23.4* or 36* MHz			* Lowpass Only
Host Interface	USB 2.0 (480 Mbps), micro-B (v.2.1),Type-C (v.2.3)	USB 3.0 (3.2 Gen 1, 5 Gbps), Type-C		
Output Format	RAW8	RAW16	RAW32	
Power	5V, 140 mA	5V, 240 mA	5V, 330 mA	USB Bus Power
Size (D x W x H)	67 x 25 x 15 mm	84 x 41 x 15 mm	77 x 110 x 30 mm	Including Case
Price	~ $60 *2	~ $130 *2 / $249 *4	~ $200 *2/ $550 *4	

*1 Total ≤ 500mA (FE 8CH), *2 Parts only, *3 https://www.datagnss.com/collections/evk/products/pocketsdr-gnss-receiver

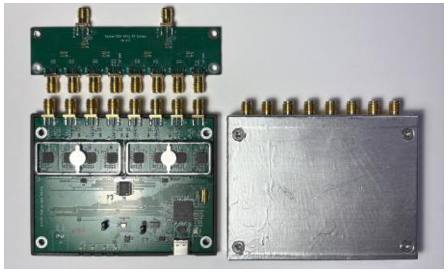
Prototype
v. 1.1 (2019.5)

FE 2CH
v. 2.1 (2021.10) v. 2.0 (2021.10)

Prototype
v. 1.4 (2021.9) v. 1.3 (2019.7)

FE 2CH
v. 2.1 (2021.10) v. 2.3 (2024.2)

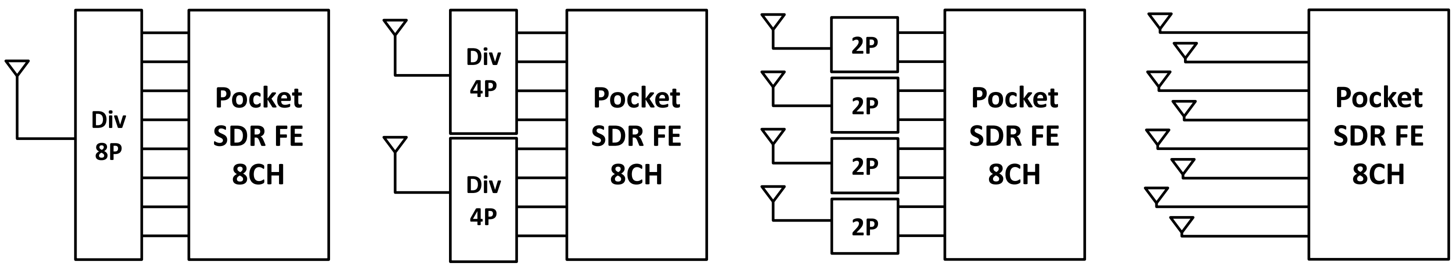
FE 4CH
v. 3.0 (2024.5)



FE 8CH
v. 4.0
(2024.11)

Pocket SDR FE 8CH (1/3)

- **Configurable by External RF-dividers**



All L-band GNSS receiver (L1+B1+G1+L2+G2+L5+ E5b/B2+B3/L6)

GNSS-compass (qual-freq.)

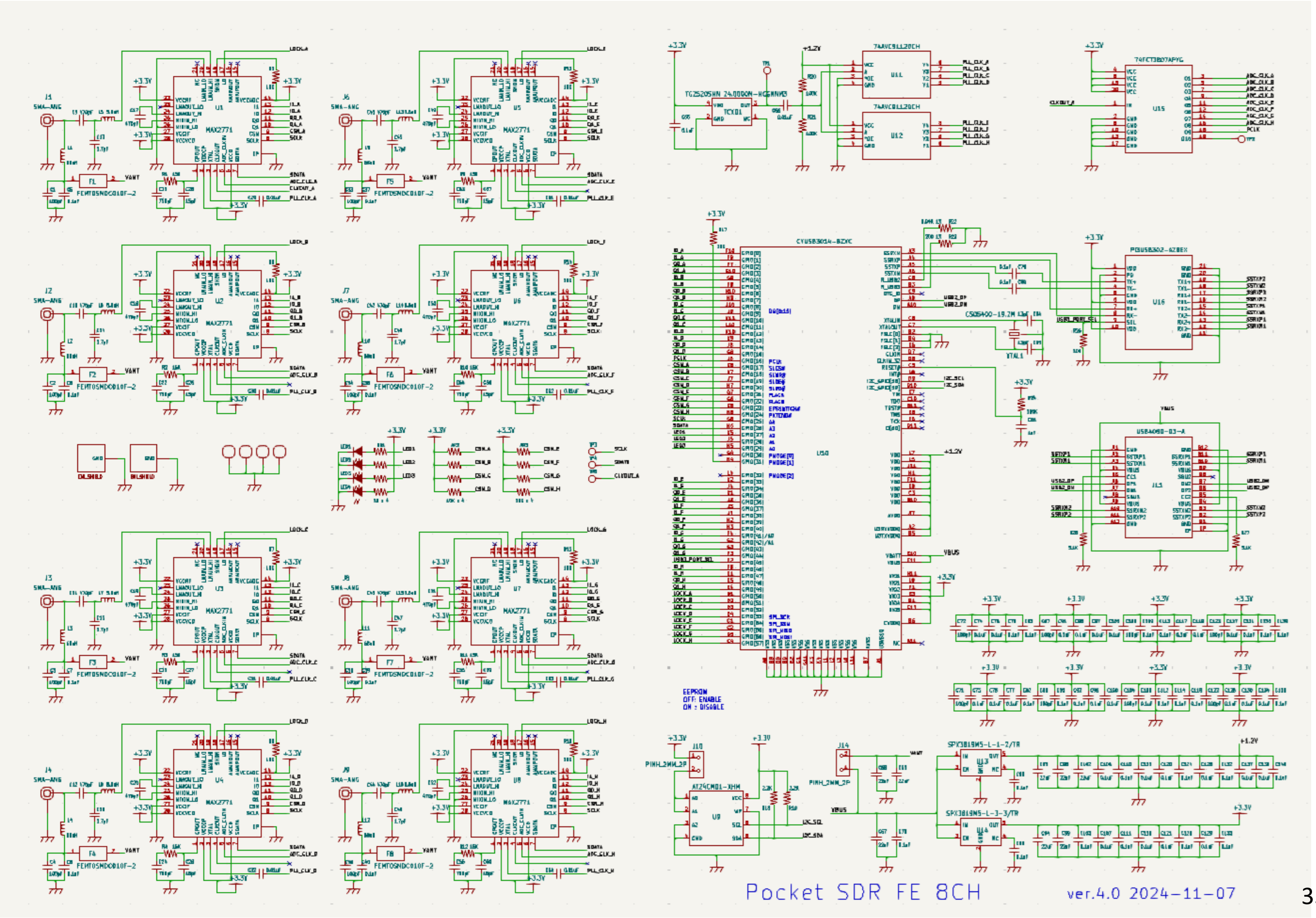
4-elements Antenna-array (dual-freq.)

8-elements Antenna-array (single-freq.)

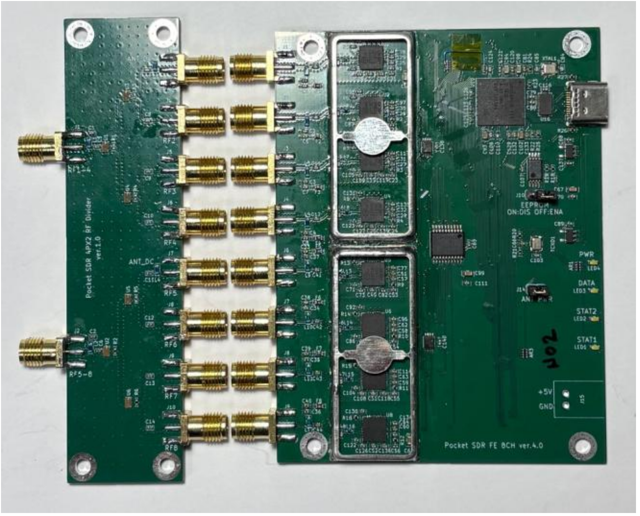
- **Parts Cost**

	A	B	C	E	F	G	H	J	K	L
1	No	Reference	Value	Qty	Assy	Supplier	Supplier Part #	Price	Total	URL
38	37	J11	USB Type-C Receptacle USB 3.2	1	1	GCT	USB4080-03-A	226.0	226.0	https://www.digikey.jp/
39	38	J12,J13	2-PIECE SHIELD Frame	2	0	Masach	MS448-10F	234.0	468.0	https://www.digikey.jp/
40	39	J12-S,J13-S	2-PIECE SHIELD Cover	2	0	Masach	MS448-10C	230.0	460.0	https://www.digikey.jp/
41										
42		Subtotal		233	217				26836.5	
43										
44	41	PCB	FR-4, 4-layer	1	0	JLCPCB		784.5	784.5	5pcs + metal mask
45	42	CASE BODY	MX3 mobile case	1	0	Takachi	MX3-11-8SBP	781.0	781.0	
46	43	CASE PANEL	SLA(Resin), Black, Sanding-Ger	1	0	JLC3DP		777.0	777.0	2pcs (F+B)
47										
48		Subtotal							2342.5	
49										
50		Total							29179.0	(Yen)

Pocket SDR FE 8CH (2/3)

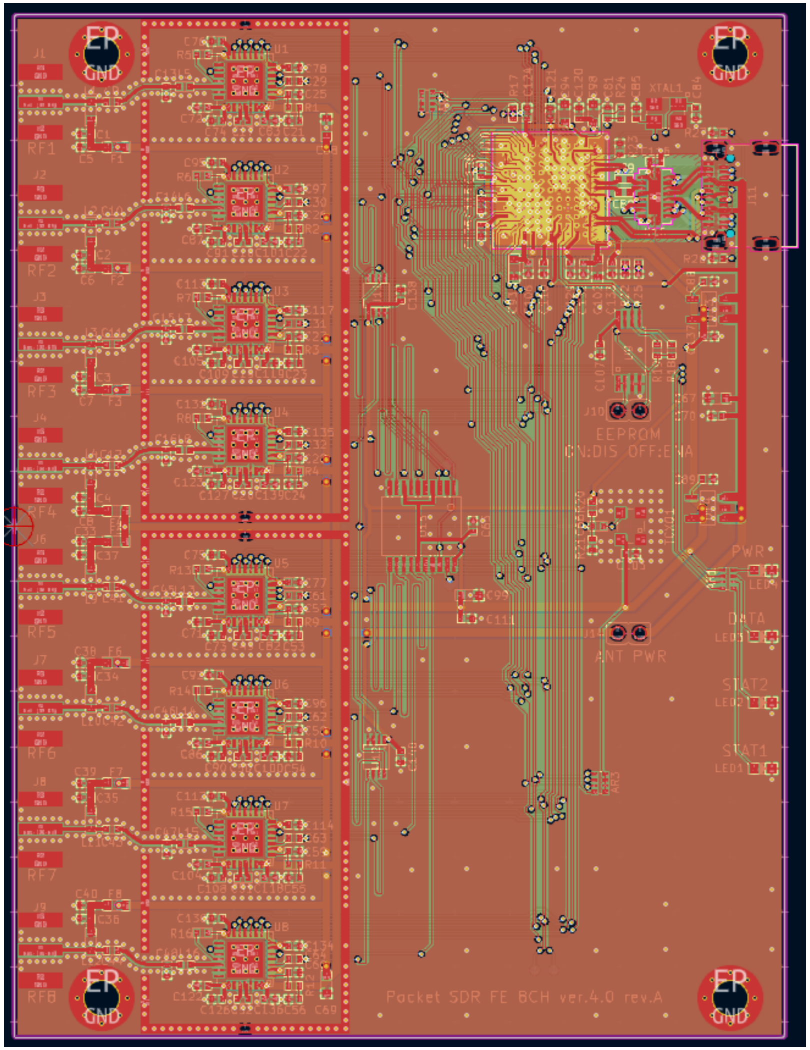


Pocket SDR FE 8CH (3/3)

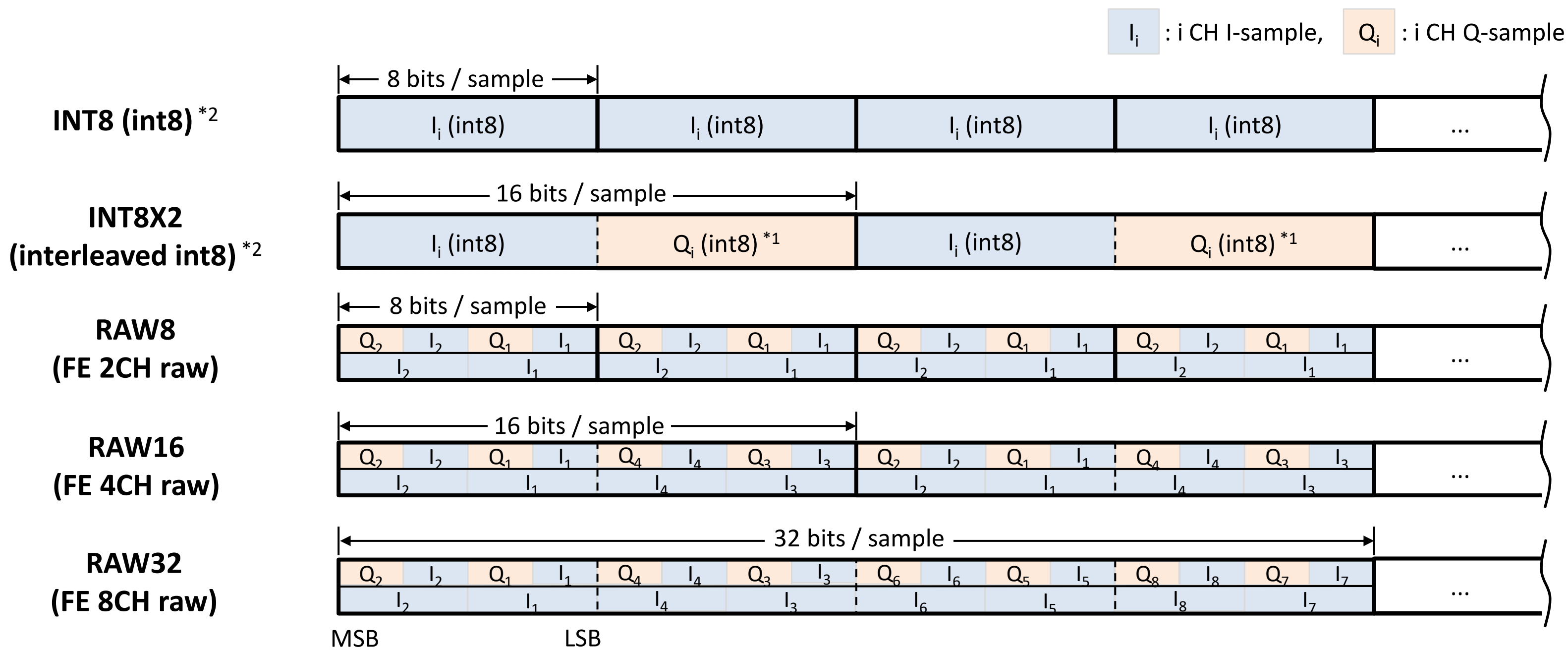


4Px2 Divider　　Pocket SDR FE 8CH

Pocket SDR FE 8CH-2ANT



IF Data Formats



2 bits IQ-sampling

bits	00	01	10	11
I	+1	+3	-1	-3
Q *1	-1	-3	+1	+3

2 bits I-sampling

bits	**00	**01	**10	**11
I	+1	+3	-1	-3

3 bits I-sampling

bits	0000	1000	0001	1001	0010	1010	0011	1011
I	+1	+3	+5	+7	-1	-3	-5	-7

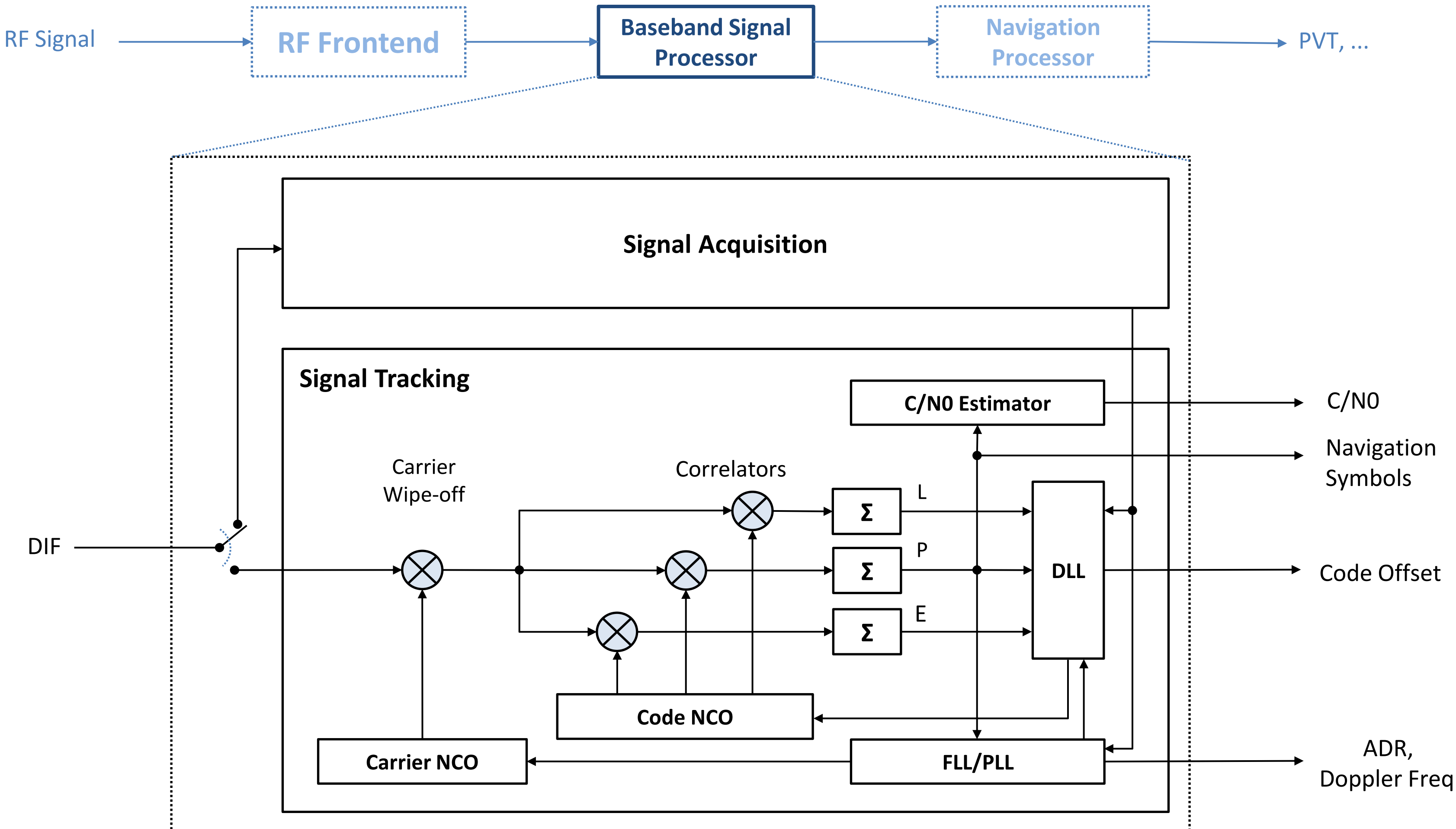
*1 Polarity inverted due to MAX2771 convention
*2 Quantized values only supported in the range [-7 ... +7]

IF Data Tag File (<path>.tag)

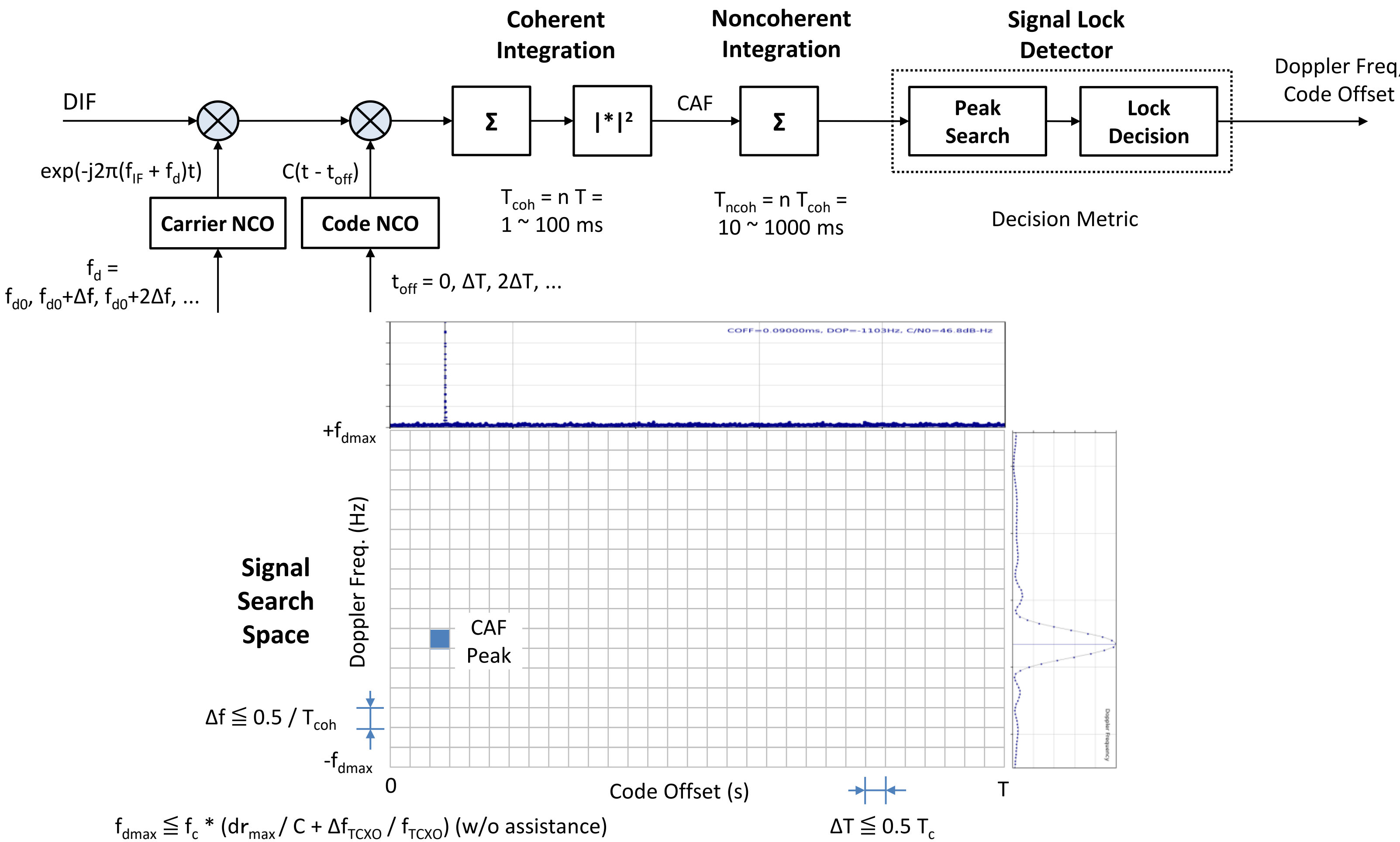
```
PROG = Pocket SDR
TIME = 2024/11/01 20:48:00.776      (Start Time GPST)
FMT  = RAW16                        (Format)
F_S  = 24                           (Sampling Freq. MHz)
F_LO = 1568,1237.8,1176.45,1278.75  (LO Freq. MHz)
IQ   = 2,2,2,2                      (Sampling, 1:I, 2:IQ)
BITS = 2,2,2,2                      (Sampling Bits)
```

Baseband Signal Processor

Baseband Signal Processor



Signal Acquisition (1/4)

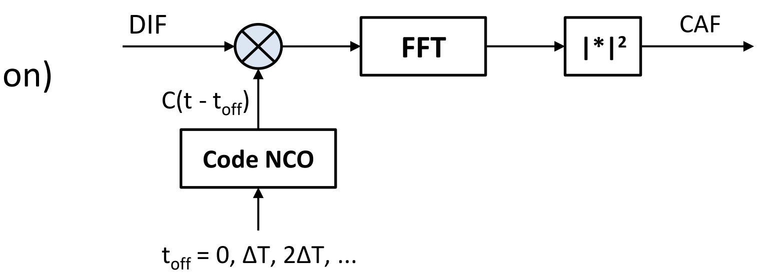


f_c: Carrier freq. (Hz), f_{IF}: IF freq. (Hz), f_d: Doppler freq. (Hz), t_{off}: Code offset (s), Δf: Frequency search step (Hz), ΔT: Code search step (s), T: Primary code cycle (s), T_{coh}: Coherent integration time (s), T_{ncoh}: Non-coherent Integration Time (s), T_c: Code chip period (s), CAF: Cross ambiguity function, dr_{max}: Max range-rate between satellite and receiver (m/s), f_{TCXO}: TCXO freq. (Hz), Δf_{TCXO}: TCXO freq. offset (Hz)

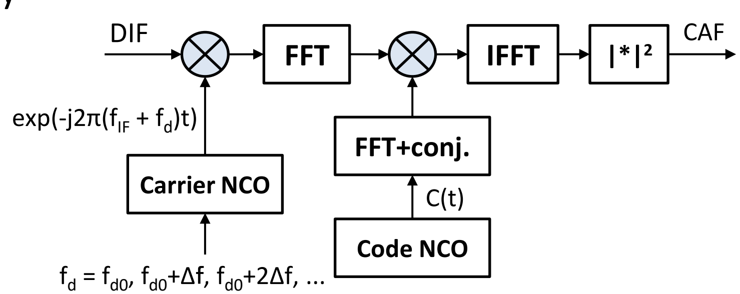
Signal Acquisition (2/4)

- **Acquisition Algorithms**
  - Serial Search (Sequential Search)
  - Parallel Freq. Search (PFS)
  - Parallel Code Phase Search (PCPS) (Circular Correlation)
  - Partial Matched Filter (PMF-FFT) [1]
  - DBZP [2], mSBZP-PCM [3], ...
- **Considerations for Acquisition Design**
  - Acquisition Time vs. Sensitivity to Weak Signal
  - Coherent vs. Noncoherent Integration Time
  - Doppler Variation including Reference Clock Instability
  - Bit-Transition by Navigation Data or Secondary Code
  - Ambiguous Peak Search for BOC-Modulation
- **Assisted Acquisition**
  - Warm-Start with Almanac and Coarse Time/Position
  - Re-Acquisition with Coarse Doppler and Code Offset
  - External Assisted Information by A-GNSS
  - Multi-Stage Search Strategy with Multiple Signals

Parallel Freq. Search (PFS)



Parallel Code Phase Search (PCPS)

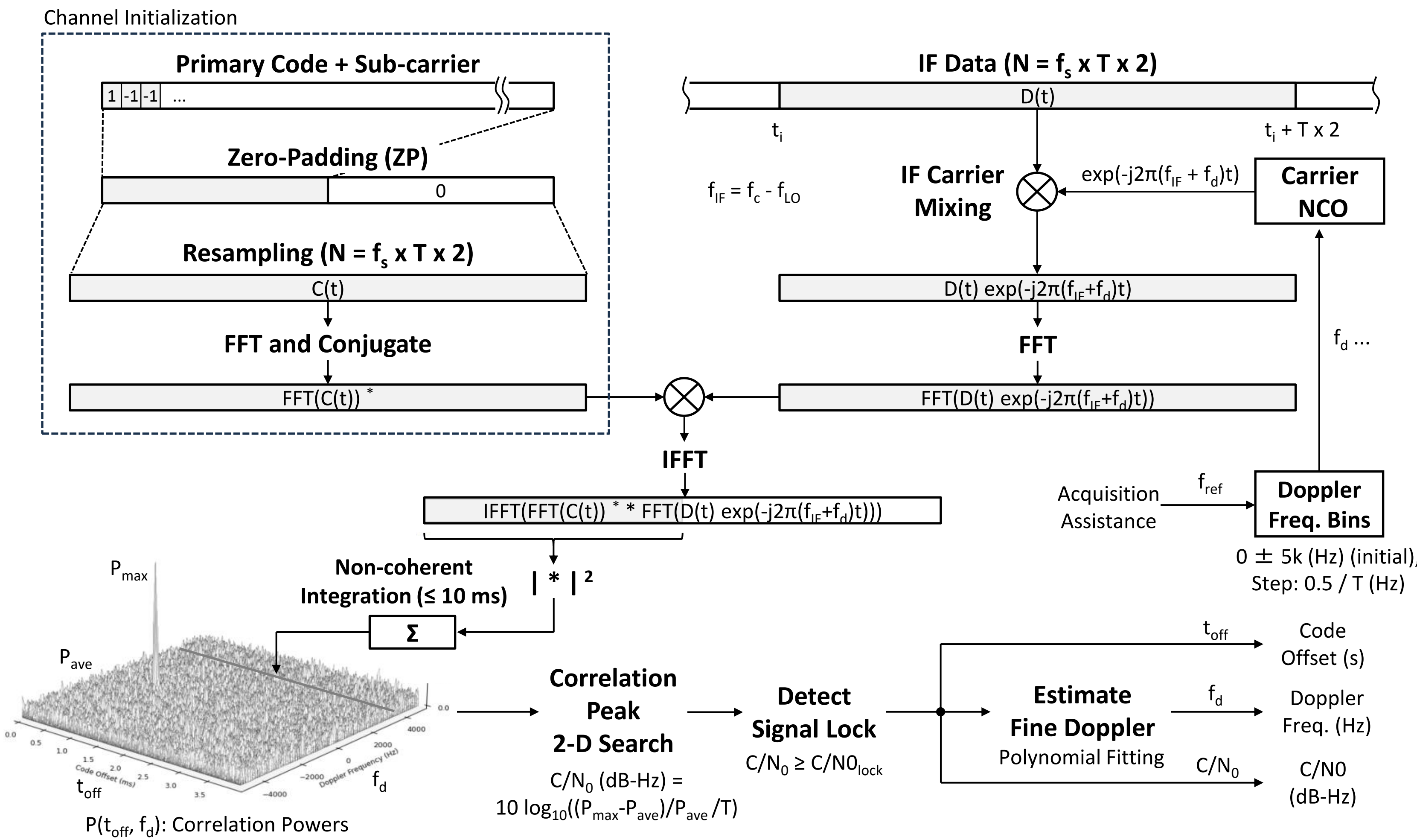


$\mathcal{F}(\mathrm{Conv}(x, y)) = \mathcal{F}(x) * \mathcal{F}(y)^*$

DFT: $O(N^2)$ vs FFT: $O(N\log N)$

[1] W.Guo et al., A new FFT acquisition scheme based on partial matched filter in GNSS receivers for harsh environments, Aerospace Science and Technology, 2017, [2] D.M.Lin et al., Direct P(Y)-code acquisition algorithm for software GPS receivers, ION GPS 1999, [3] J.Svaton et al., Novel partial correlation method algorithm for acquisition of GNSS tiered signals, Navigation, 2020

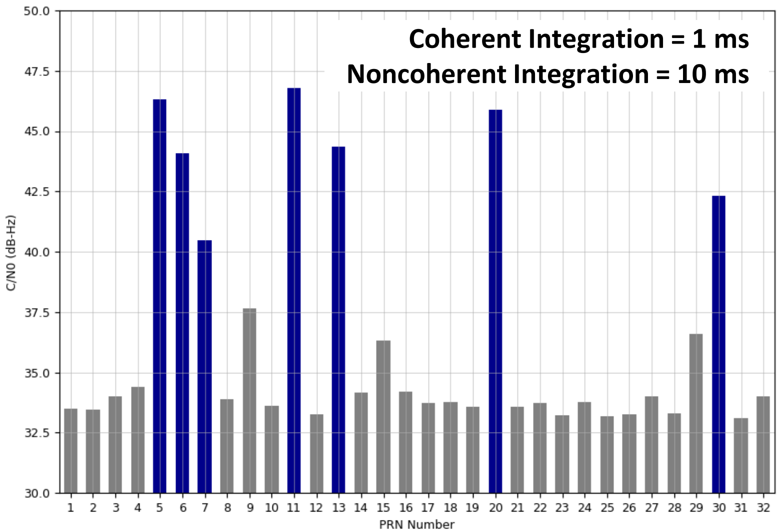
Signal Acquisition (3/4)



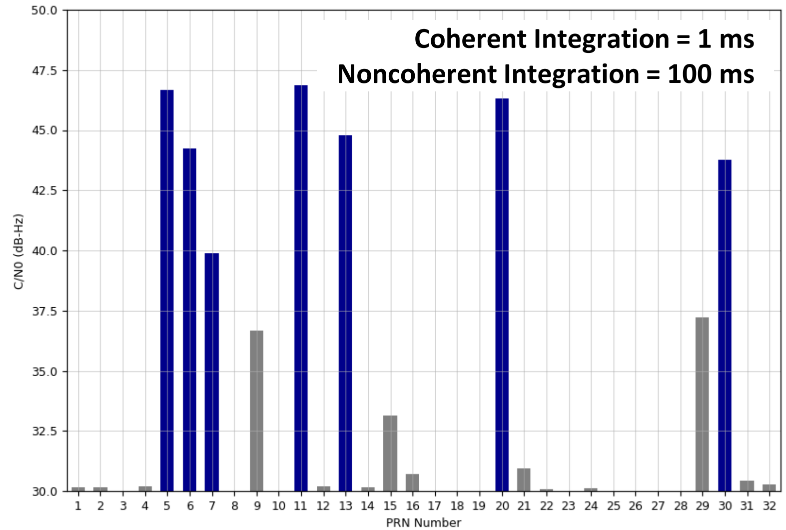
f_s: Sampling Rate (sps), T: Primary Code Cycle (s), f_{IF} : IF Carrier Freq. (Hz), f_d: Doppler Freq. (Hz), t_{off} : Code Offset (s), $C/N0_{lock}$: Lock Threshold (dB-Hz)
f_c: Carrier Freq. (Hz), f_{LO}: Local Oscillator (PLL) Freq. (Hz)

Signal Acquisition (4/4)

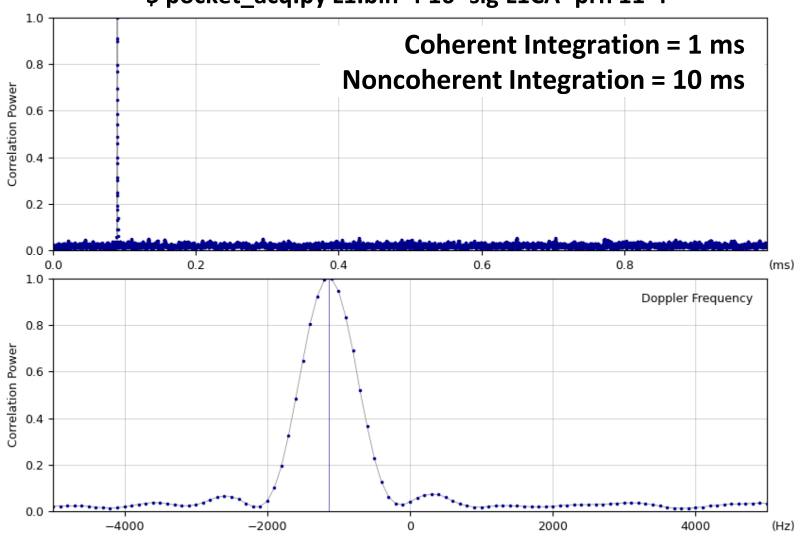
$ pocket_acq.py L1.bin -f 16 -sig L1CA -prn 1-32 -tint 10



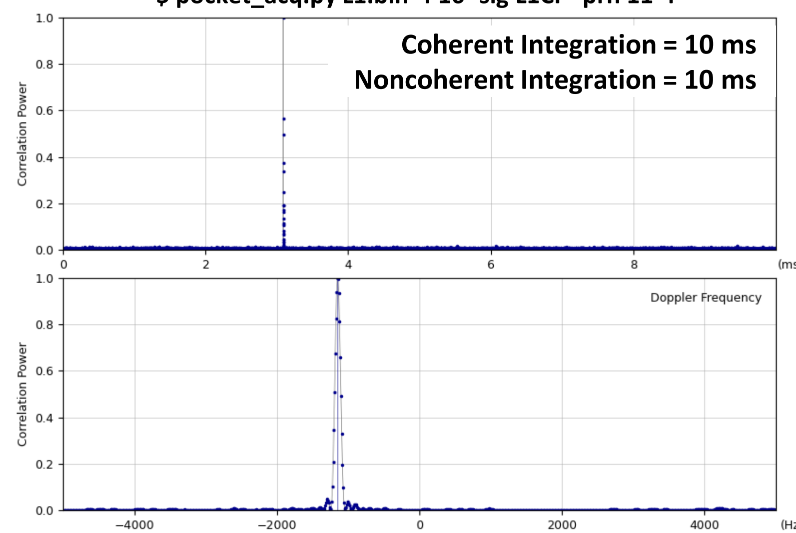
$ pocket_acq.py L1.bin -f 16 -sig L1CA -prn 1-32 -tint 100



$ pocket_acq.py L1.bin -f 16 -sig L1CA -prn 11 -l

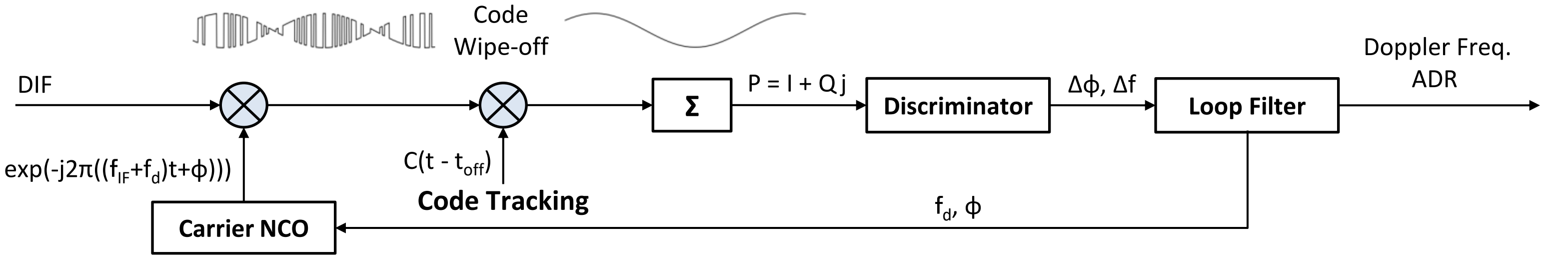


$ pocket_acq.py L1.bin -f 16 -sig L1CP -prn 11 -l



Signal Tracking (1/4)

Carrier Tracking Loop (FLL/PLL)



Discriminator

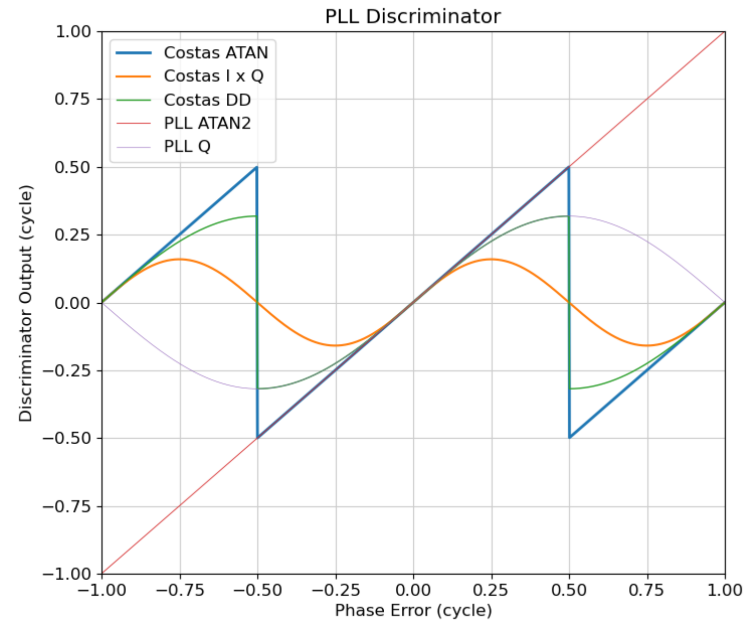
PLL

- Costas ATAN : $\Delta\phi = \mathrm{atan}(Q / I) / \pi$
- Costas I * Q : $\Delta\phi = I * Q / \pi$
- Costas sign(I) * Q : $\Delta\phi = \mathrm{sign}(I) * Q / \pi$
- PLL ATAN2 : $\Delta\phi = \mathrm{atan2}(Q, I) / \pi$
- PLL Q : $\Delta\phi = Q / \pi$

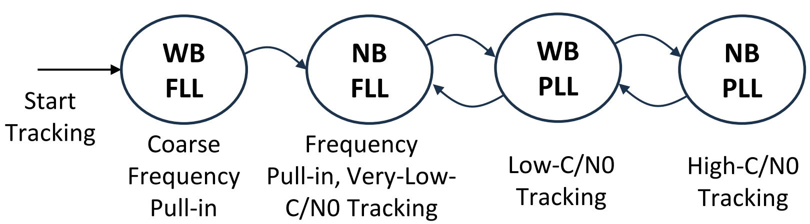
FLL

- FLL ATAN2 : $\Delta f = \mathrm{atan2}(\mathrm{dot}, \mathrm{cross}) / (t_2 - t_1) / 2\pi$
- FLL cross : $\Delta f = \mathrm{cross} / (t_2 - t_1) / 2\pi$
- FLL sign(dot) *cross : $\Delta f = \mathrm{sign}(\mathrm{dot}) * \mathrm{cross} / (t_2 - t_1) / 2\pi$

($\mathrm{dot} = I_1 * I_2 + Q_1 * Q_2$, $\mathrm{cross} = I_1 * Q_2 - I_2 * Q_1$)

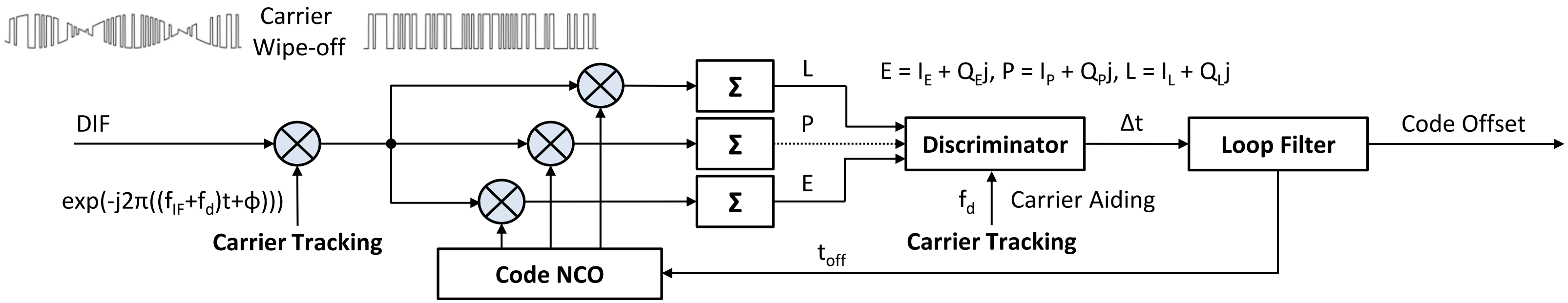


State Transition of Tracking Loop



Signal Tracking (2/4)

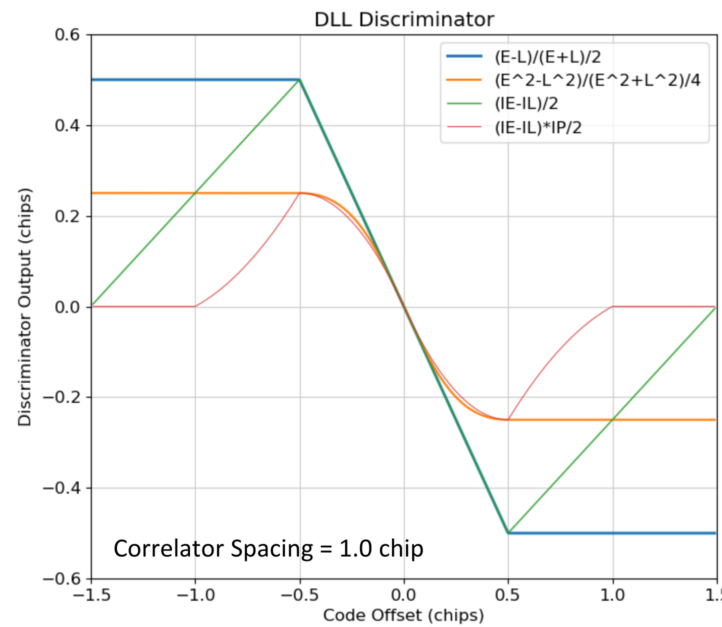
Code Tracking Loop (DLL)



Discriminator

DLL
- Noncoherent E - L : $\Delta t = 1 / 2 * (E - L) / (E + L) * T_c$
- Noncoherent $E^2 - L^2$: $\Delta t = 1 / 4 * (E^2 - L^2) / (E^2 + L^2) * T_c$
- Coherent E - L : $\Delta t = 1 / 2 * (I_E - I_L) * T_c$
- Coherent (E - L) * P : $\Delta t = 1 / 2 * (I_E - I_L) * I_P * T_c$

$(E = \mathrm{sqrt}(I_E^2 + Q_E^2), L = \mathrm{sqrt}(I_L^2 + Q_L^2))$



Multipath Mitigation

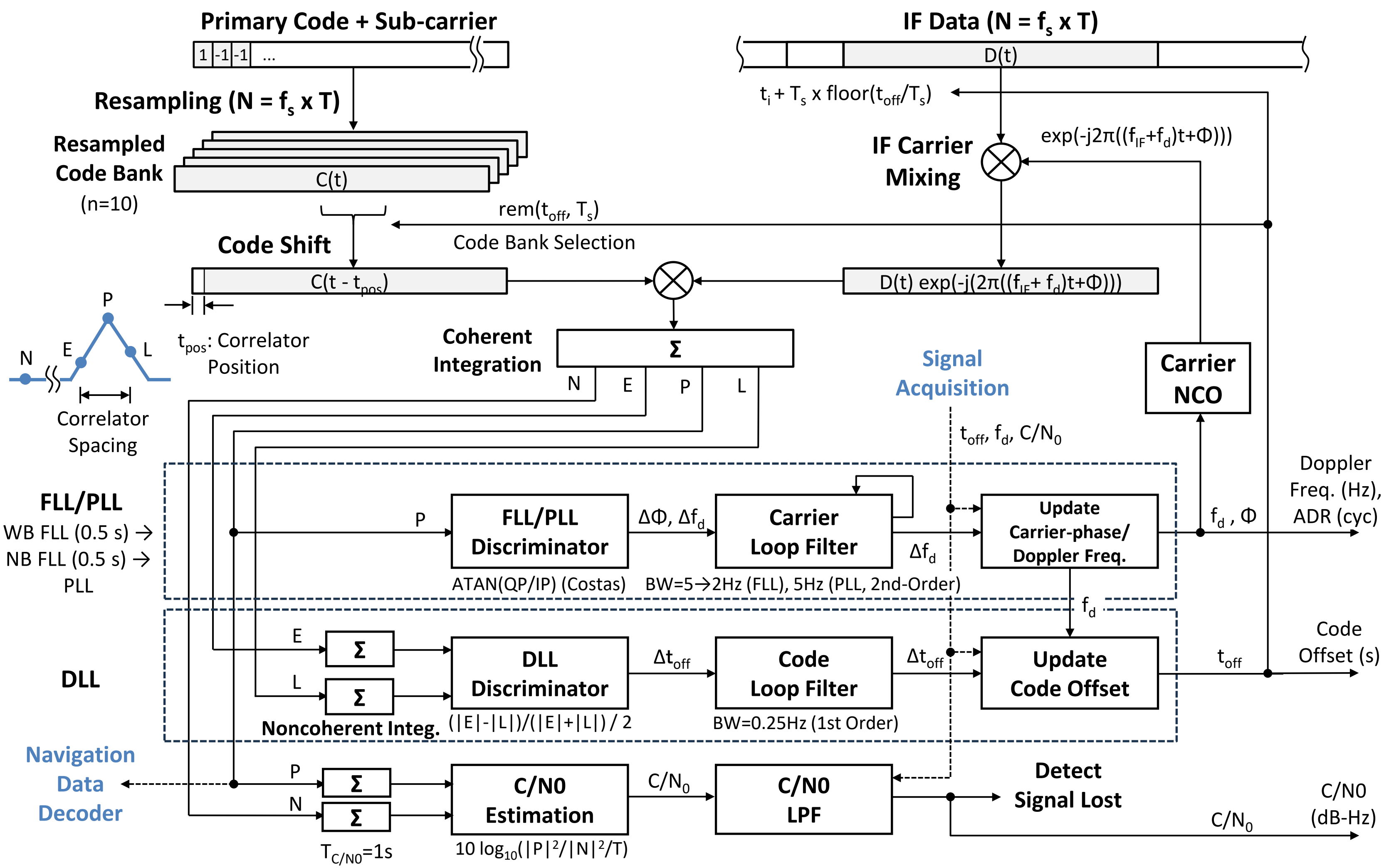
- Narrow Correlator (spacing = 0.01 ~ 0.1 chip)
- Double-Delta Correlator (E2+E1+P+L1+L2 Correlators)
- Strobe Correlator [1]
- MEDLL (Multipath Estimating DLL) (> 10 Correlators) [2]
- VDLL (Vector DLL), Deeply-Coupled INS Integration, ...

Side Peak Tracking for BOC

- Bump-jumping (BJ)
- Astrium Correlator, Double Correlator, ASPeCT, SCM, SLC, ...

[1] L.Garin et al., Strobe & edge correlator multipath mitigation for code, ION GPS 1996
[2] B.R.Townsend et al., Performance evaluation of the multipath estimating delay lock loop, Navigation 1995

Signal Tracking (3/4)

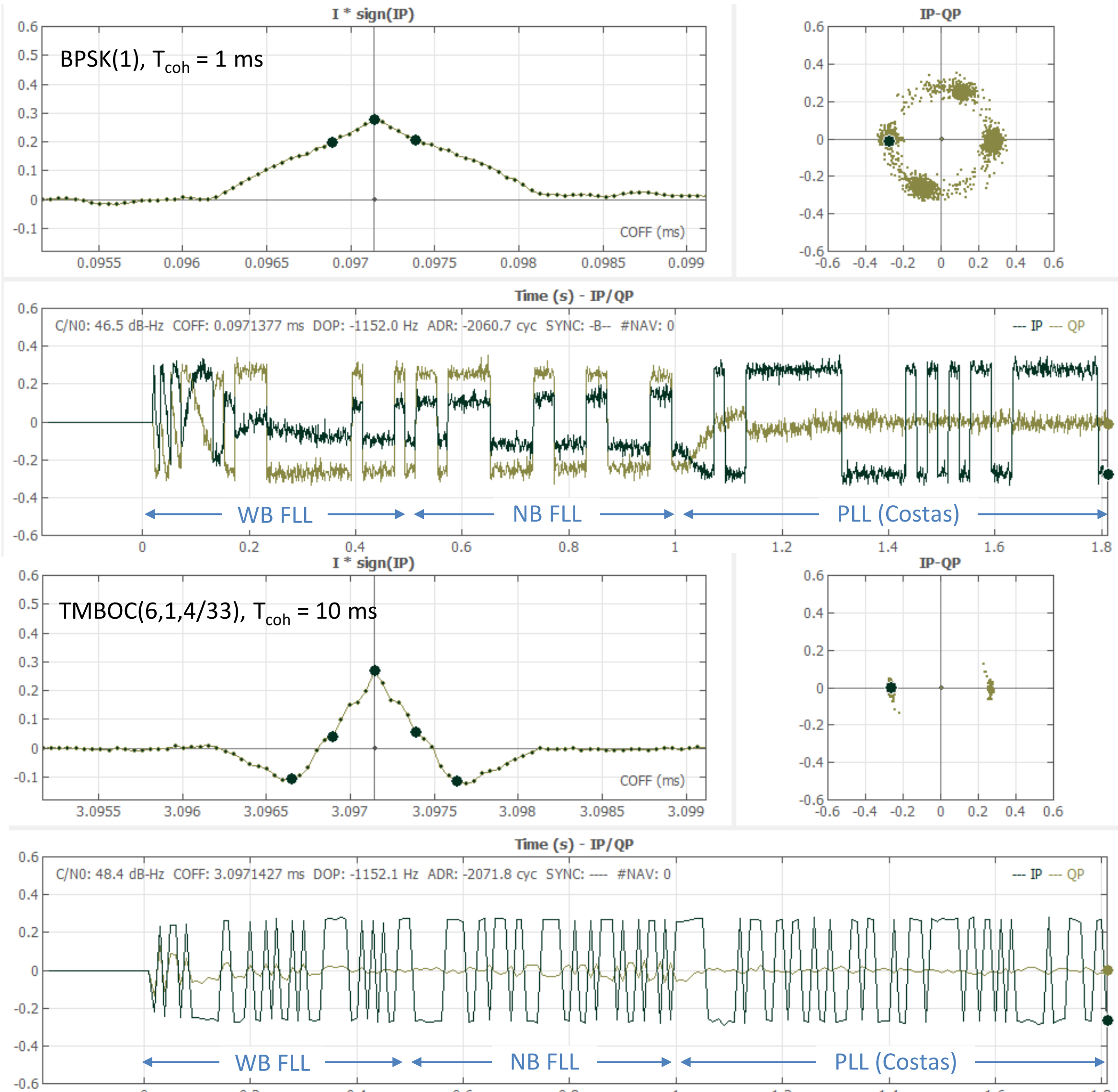


E/P/L/N: Early/Prompt/Late/Noise Correlation, f_s: Sampling Rate (sps), T_s: Sampling Cycle (s), T: Primary Code Cycle (s), f_{IF} : IF Carrier Freq. (Hz), f_d: Doppler Freq. (Hz), t_{off} : Code Offset (s), Φ: Carrier-phase (cyc), Δf_d: Doppler Error (Hz), Δt_{off}: Code Offset Error (s), ΔΦ: Carrier-phase Error (cyc)

Signal Tracking (4/4)

GPS PRN11 L1C/A

GPS PRN11 L1Cp



FLL/PLL

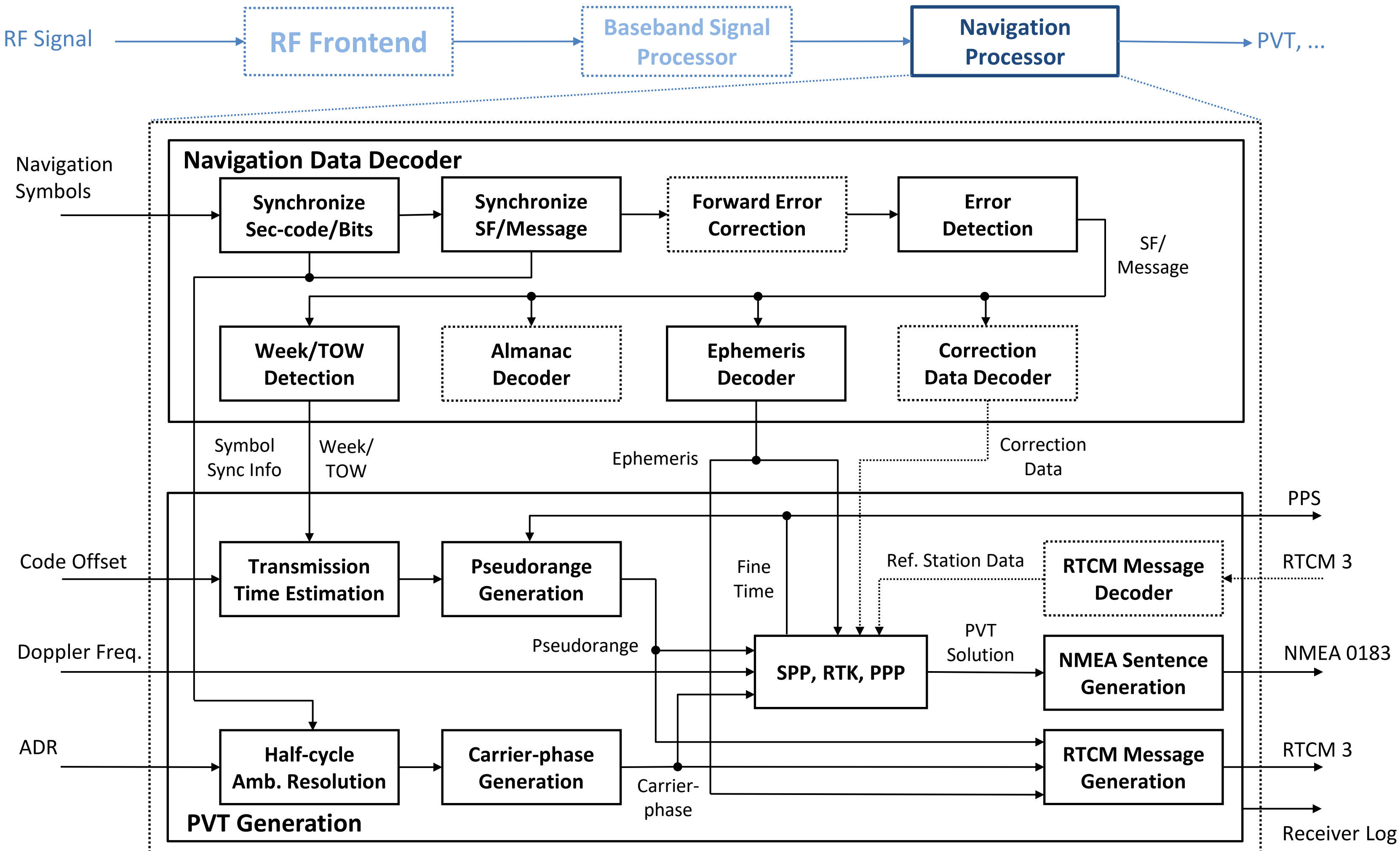
FLL Loop Filter BW = 5Hz (WB), 2Hz (NB)
PLL Loop Filter BW = 10Hz

DLL

DLL Loop Filter BW = 0.5 Hz
T_{ncoh} = 20 ms

Navigation Processor

Navigation Processor



PVT: position, velocity and timing, SF: subframe, SPP: single point positioning, RTK: Real-time kinematic, PPP: Precise point positioning

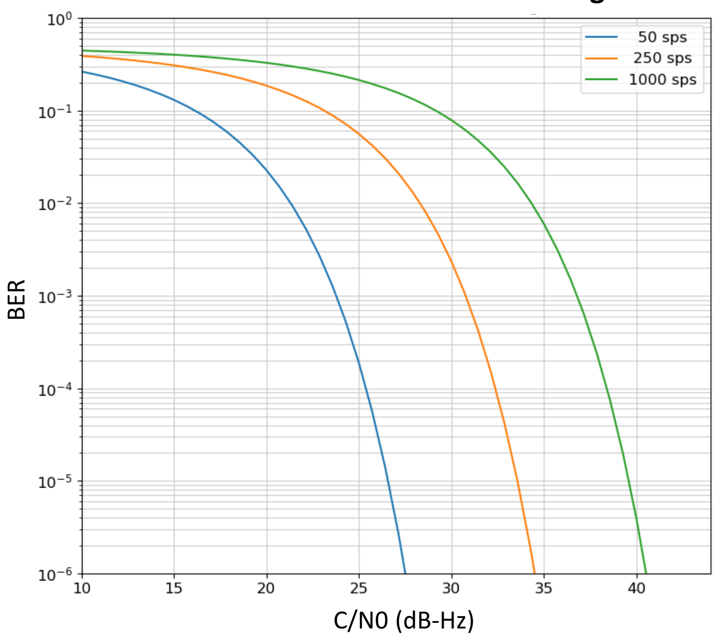
Navigation Data

System	Signal	Navigation Data	Frame/Subframe/Page/Message			Error Detection and Correction
			Cycle (s)	Sync (syms)	Data Structure (bits)	
GPS, QZSS	L1C/A	LNAV	30/6	8	(24 + 6 (parity)) (word) x 10	Hamming(32,26)
	L2C, L5Q	CNAV	12	8	8 (sync) + 268 + 24 (CRC)	1/2(600,300), CRC24
	L1Cd	CNAV-2	18	52	9 (SF1) + 600 (SF2) + 274 (SF3)	BCH(52,9), BI(38x46), LDPC(1200,600), LDPC(548,274), CRC24
GLONASS	L1C/A, L2C/A	GLO-STR	150/30/2	30	1 + 76 + 8 (parity)	Hamming(84,76)
	L3OCd	GLO-L3-STR	3	20	20 (sync) + 256 + 24 (CRC)	1/2(600,300), CRC24
	L1OCd	GLO-L1-STR	2	12	12 (sync) + 222 + 16 (CRC)	1/2(500,250) , CRC16
Galileo	E1C, E5b-I	I/NAV	720/30/2	10	114 + 6 (Tail) (even)	BI(30x8), 1/2(250,125), CRC24
					82 + 24 (CRC) + 8 + 6 (Tail) (odd)	
	E5a-I	F/NAV	600/50/10	12	214 + 24 (CRC) + 6 (Tail)	BI(61x8), 1/2(500,250) , CRC24
	E6B	C/NAV	1	16	14 + 448 (page) + 24 (CRC) + 6 (Tail)	BI(123x8), 1/2(1000,500), CRC24, HPVRS(HAS)
QZSS	L1S	L1S	1	8 x 3	8 (sync) + 218 + 24 (CRC)	1/2(500,250), CRC24
	L6D, L6E	L6D, L6E	1	32	32 (sync) + 17 + 1695 + 256 (RS)	RS(255,223)
BeiDou	B1I, B2I, B3I	D1	720/30/6	11	(26 + 4 (parity)) + (22 + 8 (parity)) x 9	BI(30x10), BCH(15,11,1)
		D2	360/3/0.6			
	B1C-D	B-CNAV1	18	72	14 (SF1) + 600 (SF2) + 264 (SF3)	BCH(21,6), BCH(51,8), BI(36x48), 64ary-LDPC(200,100), 64ary-LDPC(88,44), CRC24
	B2a-D	B-CNAV2	3	24	264 + 24 (CRC)	64ary-LDPC(96,48), CRC24
	B2b-I	B-CNAV3	1	28	462 + 24 (CRC)	64ary-LDPC(162,81), CRC24
		B2b-PPP				
NavIC	L1-SPS	IRN-L1-NAV	52/18	52	9 (SF1) + 600 (SF2) + 274 (SF3)	BCH(52,9), BI(46x38), LDPC(1200,600), LDPC(548,274), CRC24
	L5-SPS, S-SPS	IRN-NAV	12	16	262 + 24 (CRC) + 6 (Tail)	BI(73x8), 1/2(572,286), CRC24
SBAS	L1C/A	SBAS	1	8 x 3	8 (sync) + 218 + 24 (CRC)	1/2(500,250), CRC24
	L5I	L5 SBAS	1	4 x 6	4 (sync) + 222 + 24 (CRC)	1/2(500,250), CRC24

1/2: Convolutional Code (R=1/2, K=7), BI: Block Interleave, LDPC: Low Density Parity Check, RS: Reed-Solomon, CRC: Cyclic Redundancy Check, HPVRS (High Parity Vertical Reed-Solomon): 24 (header) + 424 (page), 424 x 32 -> RS(255,32,224) -> 424 x 255 -> transmitted by different sats.)

Error Detection and Correction

Bit Error Rate of Uncoded BPSK Signal



$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{C}{N_0}T_b}\right)$$

- **Error Detection**
  - Hamming Code (GPS/QZSS L1C/A)
  - CRC24 (GPS/QZSS L2C, ...)
  - CRC16 (GLONASS L1OC)
- **Forward Error Correction (FEC)**
  - Hamming Code (GLONASS L1C/A, L2C/A)
  - Reed-Solomon (RS) Code (QZSS L6D/E, Galileo E6/HAS)
  - BCH Code (GPS/QZSS L1C, BDS B1I/B2I/B3I)
  - Convolutional Code (R=1/2, K=7) (GPS/QZSS L2C, ...)
  - LDPC Code (GPS/QZSS L1C, NavIC L1-SPS)
  - NB (64ary)-LDPC Code (BDS B1C, B2a/b)
  - Block Interleave (BI) (GPS/QZSS L1C, ...)
- **FEC Decoder Algorithms**
  - Convolutional Code: Viterbi Algorithm [1]
  - Reed-Solomon Code: Berlekamp-Massey Algorithm [2][3]
  - LDPC Code: Sum-product, Min-sum Algorithm [2][4]
  - NB-LDPC Code: EMS (extended-min-sum) Algorithm [5]

erfc(): Complementary error function, E_b/N_0: Bit energy to noise density, T_b: Bit period (s)

[1] A.J.Viterbi. Error bounds for convolutional codes and an asymptotically optimum decoding algorithm, IEEE Trans. on Information Theory, 1967
[2] CCSDS 131-B-5, Recommendation for Space Data System Standard, TM Synchronization and Channel Coding - Blue Book, September 2023
[3] E.Berlekamp, Algebraic Coding Theory - Revised Edition, World Scientific Publishing, 2015
[4] X-Y.Hu et al., Efficient implementations of the sum-product algorithm for decoding LDPC codes, IEEE Global Telecomm Conference, 2001
[5] E.Li et al., Trellis-based Extended Min-Sum algorithm for non-binary LDPC codes and its hardware structure, IEEE Trans. on Communications, 2013

PVT Generation

- **Observation Data Generation**
  - Generate pseudorange with week/TOW and code offset (data signals)
  - Resolve code-cycle ambiguity by secondary code phase (pilot signals)
  - Resolve secondary-code-cycle ambiguity by data signal pseudorange (pilot signals)
  - Generate carrier-phase with ADR
  - Resolve half-cycle ambiguity by symbol-sync info
  - Receiver clock steering with fine-time generated by PVT
- **PVT Solution**
  - SPP (single point positioning) by pseudorange with or without SBAS correction data
  - RTK by carrier-phase/pseudorange and reference station data
  - PPP by carrier-phase /pseudorange and correction data for PPP
  - PVT algorithms base on RTKLIB [1]
- **Message Generation**
  - NMEA 0183 (GNRMC, GNGGA, GNGSA, GxGSV, ... sentences) [2]
  - RTCM 3 MSM (MT1077, 1087, 1097, 1117, 1127, 1137, 1107) with extensions [3]
  - RTCM 3 EPH (MT1019, 1020, 1045, 1046, 1044, 1042, 1041) (decoded ephemeris) [3]
  - Receiver Log

NMEA GNRMC: Recommended minimum specific GNSS data, GNGGA: Global positioning fix data,
GNGSA: GNSS DOP and active satellites, GxGSV: GNSS satellites in view

[1] RTKLIB ver. 2.4.2 Manual, 2013, [2] NMEA 0183, Standard for interfacing electronic devices version 4.10, 2012,
[3] RTCM standard 10403.4, Differential GNSS (global navigation satellite system) services - version 3, November 2024

RTCM 3

RTCM 3 Message [1]

Preamble(8)	000000	Length(10)	Data (Length x 8)	CRC (24)

MT(12)	Message Body	(bits)

Message		MT (Message Type)						
		GPS	**GLONASS**	**Galileo**	**QZSS**	**BeiDou**	**NavIC**	**SBAS**
OBS	Basic RTK L1 Only	1001	1009	-	-	-	-	-
	Extended RTK L1 Only	1002	1010	-	-	-	-	-
	Basic RTK L1 & L2	1003	1011	-	-	-	-	-
	Extended RTK L1 & L2	1004	1012	-	-	-	-	-
Satellite Ephemeris Data		1019	1020	1045, 1046*2	1044	1042	1041	-
MSM	MSM 1 (Compact P) *3	1071	1081	1091	1111	1121	1131	1101
	MSM 2 (Compact PR) *3	1072	1082	1092	1112	1122	1132	1102
	MSM 3 (Compact P+PR) *3	1073	1083	1093	1113	1123	1133	1103
	MSM 4 (Full P+PR+CN) *3	1074	1084	1094	1114	1124	1134	1104
	MSM 5 (Full P+PR+PRR+CN) *3	1075	1085	1095	1115	1125	1135	1105
	MSM 6 (Full P+PR+CN+H) *3	1076	1086	1096	1116	1126	1136	1106
	MSM 7 (Full P+PR+PRR+CN+H) *3	1077	1087	1097	1117	1127	1137	1107
SSR	Orbit Correction	1057	1063	1240*1	1246*1	1258*1	-	1252*1
	Clock Correction	1058	1064	1241*1	1247*1	1259*1	-	1253*1
	Code Bias	1059	1065	1242*1	1248*1	1260*1	-	1254*1
	Combined Orbit and Clock	1060	1066	1243*1	1249*1	1261*1	-	1255*1
	URA	1061	1067	1244*1	1250*1	1262*1	-	1256*1
	High-Rate Clock Correction	1062	1068	1245*1	1251*1	1263*1	-	1257*1
Station Coordinates/Antenna Description		1005, 1006, 1007, 1008, 1032, 1033						
Proprietary Information		4070 ~ 4095						

*1 Draft version, *2 1045: F/NAV, 1046: I/NAV, *3 P: Pseudorange, PR: PhaseRange, PRR: PhaseRangeRate, CN: CNR, H: High Resolution

[1] RTCM standard 10403.4, Differential GNSS (global navigation satellite system) services - version 3, November 2024

Implementation of Pocket SDR

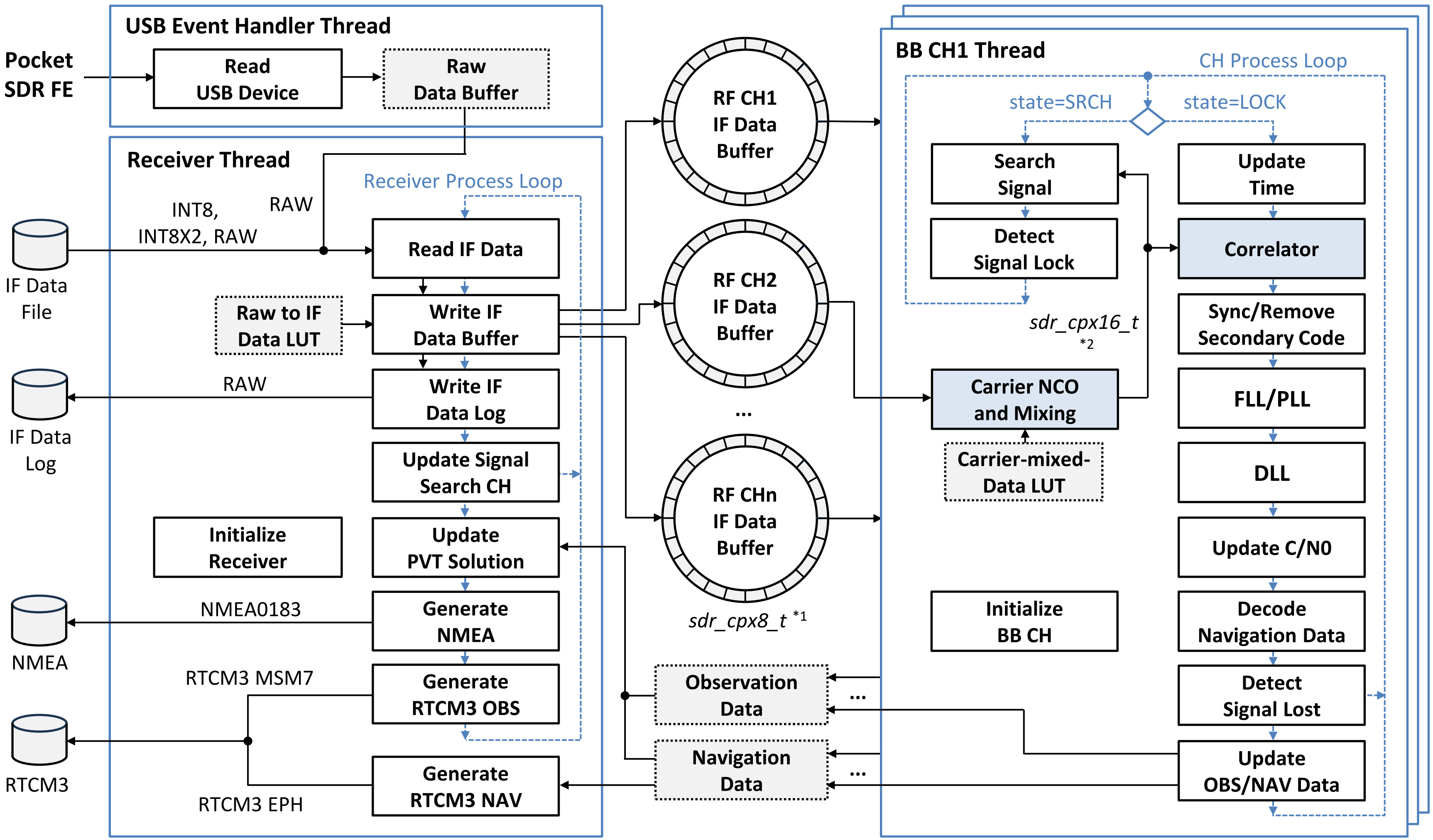
Pocket SDR Features

- **Supported System and Signals**
  - GPS: L1C/A, L1C-D, L1C-P, L2C-M, L5-I, L5-Q
  - GLONASS: L1C/A (L1OF), L2C/A (L2OF), L1OCd, L1OCp, L2OCp, L3OCd, L3OCp
  - Galileo: E1-B, E1-C, E5a-I, E5a-Q, E5b-I, E5b-Q, E6-B, E6-C
  - QZSS: L1C/A, L1C/B, L1C-D, L1C-P, L1S, L2C-M, L5-I, L5-Q, L5S-I, L5S-Q, L6D, L6E
  - BeiDou: B1I, B1C-D, B1C-P, B2a-D, B2a-P, B2I, B2b-I, B3I
  - NavIC: L1-SPS-D, L1-SPS-P, L5-SPS, (S-SPS)
  - SBAS: L1C/A, L5-I, L5-Q
- **Supported RF Frontends**
  - Pocket SDR FE 2CH, FE 4CH and FE 8CH, ... (planned)
- **Supported Environments**
  - Windows 10/11, Linux (Ubuntu, ...), macOS (Apple silicon), Raspberry Pi 4/5 (RasPi OS), ...
- **Program Languages**
  - C/C++ (gcc or clang)
  - Python 3 (numpy, scipy, matplotlib and TKinter)
- **External libraries**
  - CyAPI or libusb-1.0 (USB device driver)
  - FFTW3 (FFT/IFFT), LIBFEC and LDPC-code (FEC decoder), RTKLIB (PVT, NAV data decoder, ...)

Pocket SDR Package

```
PocketSDR    ─┬─ bin         # Pocket SDR APs binary programs
(ver.0.14)    ├── app         # Pocket SDR APs source programs
              │   ├── pocket_conf  # Pocket SDR FE device configurator
              │   ├── pocket_dump  # Dump digital IF data of Pocket SDR FE device
              │   ├── pocket_scan  # Scan and list USB devices
              │   ├── pocket_acq   # GNSS signal acquisition
              │   ├── pocket_trk   # GNSS signal tracking and PVT generation
              │   ├── pocket_snap  # Snapshot Positioning
              │   └── convbin      # RINEX converter supporting Pocket SDR
              ├── src         # Pocket SDR library source programs
              ├── python      # Pocket SDR Python scripts
              ├── lib         # Libraries for APs and Python scripts
              │   ├── win32        # Libraries for Windows
              │   ├── macos        # Libraries for mac OS
              │   ├── linux        # Libraries for Linux or Raspberry Pi OS
              │   ├── build        # Makefiles to build libraries
              │   ├── cyusb        # Cypress EZ-USB API (CyAPI.a) and includes
              │   └── RTKLIB       # RTKLIB source programs based on 2.4.3 b34
              ├── conf        # Configuration files for Pocket SDR FE
              ├── FE_2,4,8CH  # Pocket SDR FE 2CH, 4CH, 8CH H/W and F/W
              ├── driver      # Driver installation instruction for Pocket SDR FE
              ├── doc         # Documents
              ├── image       # Image files for documents
              ├── sample      # Sample digital IF data captured by Pocket SDR FE
              └── test        # Test codes and data
```

Pocket SDR S/W Structure



Control Flow Data Flow

*1 (4 + 4) bits Fixed Point Complex
*2 (8 + 8) bits Fixed Point Complex

Optimization (1/4)

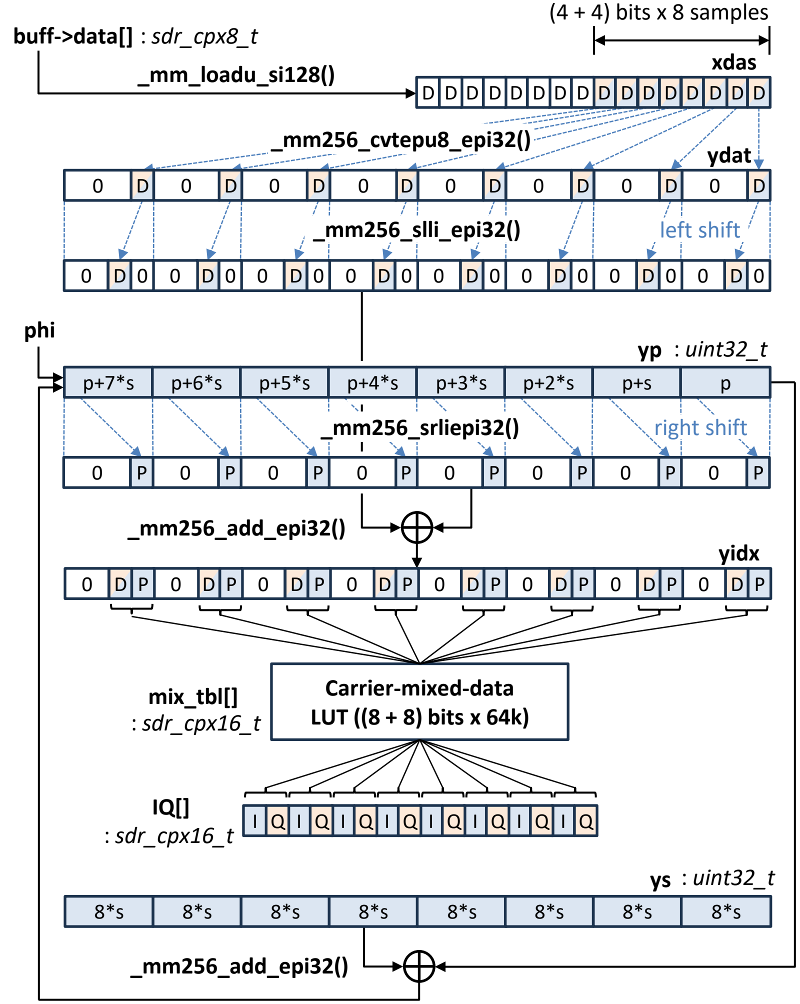
- **Reduction of Memory Bandwidth**
  - Minimized size of IF data (8 bits and 16 bits fixed-point complex)
  - Minimized data copy
- **Usage of Pre-initialized Lookup Table (LUT)**
  - Conversion of raw input data to IF data buffer
  - Carrier-mixing (multiplication of IF carrier-replica and IF data buffer)
- **Multi-threading**
  - Efficient resource utilization of multi-core CPU and SMT (simultaneous muti-threading)
  - Assignment of independent and asynchronized threads to each receiver channels
  - Minimized synchronization overhead between threads
- **SIMD Instructions**
  - Intel/AMD x86_64: SSE2 and AVX2 (128 and 256 bits-wide vector-instructions)
  - ARM: NEON (128 bits-wide vector-instructions)
  - Correlator, carrier-mixing, multiplication of complexes, ...
- **Optimized FFT/IFFT**
  - FFTW3 for SP-complex 1D-FFT/IFFT with SIMD optimization
  - FFTW wisdom for environment specific optimization

Optimization (2/4)

Carrier NCO and Mixing

PocketSDR/src/sdr_func.c (ver.0.13)

```
void mix_carr(const sdr_buff_t *buff, int ix, int N, double phi,
              double step, sdr_cpx16_t *IQ) { // step = Δphi / sample
  const uint8_t *data = buff->data + ix;
  double scale = (double)(1 << 24) * NTBL;
  uint32_t p = (uint32_t)((phi - floor(phi)) * scale); // initial phase
  uint32_t s = (uint32_t)(int)(step * scale); // phase step / sample
  int i = 0;
  __m256i yp = _mm256_set_epi32(p+s*7, p+s*6, p+s*5, p+s*4, ...);
  __m256i ys = _mm256_set1_epi32(s*8);
  for ( ; i < N - 16; i += 8) {
    int idx[8];
    __m128i xdas = _mm_loadu_si128((__m128i *)(data + i));
    __m256i ydat = _mm256_cvtepu8_epi32(xdas);
    __m256i yidx = _mm256_add_epi32(_mm256_slli_epi32(ydat, 8),
            _mm256_srli_epi32(yp, 24));
    _mm256_storeu_si256((__m256i *)idx, yidx);
    IQ[i  ] = mix_tbl[idx[0]]; // IQ(t)=data(t)*exp(-j*2*pi*(f*t+phi))
    IQ[i+1] = mix_tbl[idx[1]];
    IQ[i+2] = mix_tbl[idx[2]];
    ...
    IQ[i+7] = mix_tbl[idx[7]];
    yp = _mm256_add_epi32(yp, ys);
  }
  for (p += s * i; i < N; i++, p += s) {
    int idx = ((int)data[i] << 8) + (p >> 24);
    IQ[i] = mix_tbl[idx];
  }
}
```



_mm_*(), _mm256_*(): SSE2, AVX2 Intrinsics [1]

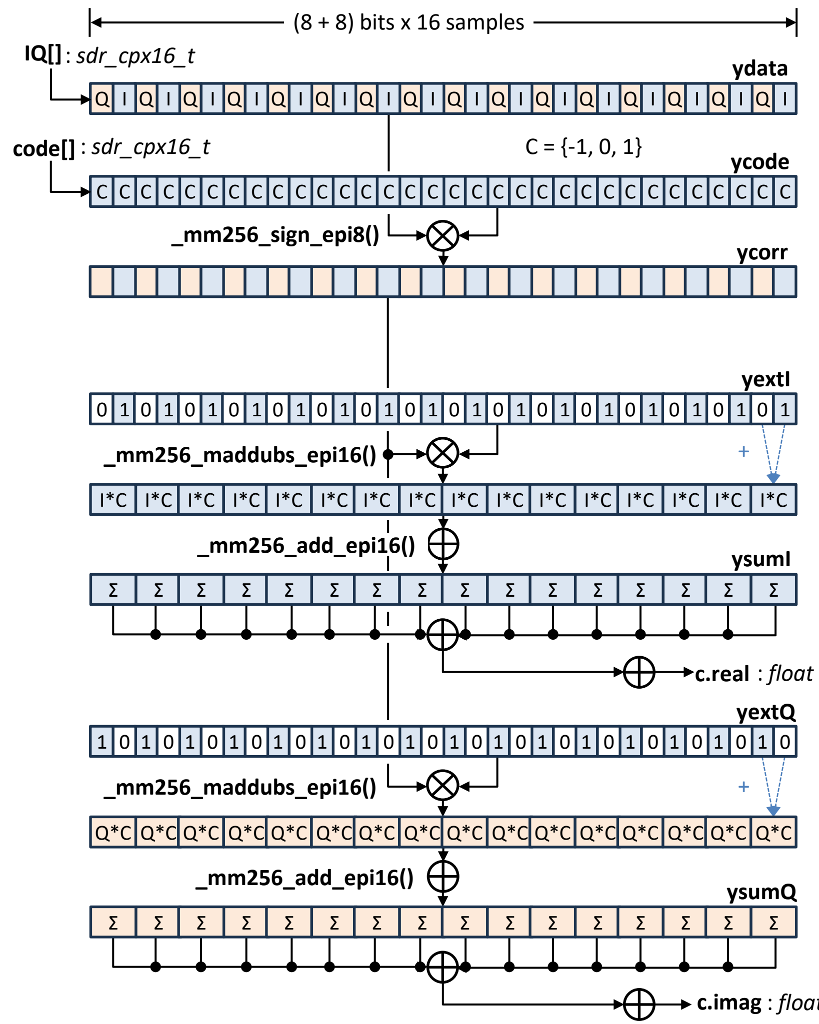
[1] https://www.intel.com/content/www/us/en/docs/intrinsics-guide/index.html

Optimization (3/4)

Correlator

PocketSDR/src/sdr_func.c

```
void dot_IQ_code(const sdr_cpx16_t *IQ, const sdr_cpx16_t *code, int N,
                 float s, sdr_cpx_t *c) { // c: correlation
  int i = 0;
  (*c)[0] = (*c)[1] = 0.0f;
  __m256i ysumI = _mm256_setzero_si256();
  __m256i ysumQ = _mm256_setzero_si256();
  __m256i yextI = _mm256_set_epi8(0,1,0,1,0,1,0,1,0,1,0,1,...);
  __m256i yextQ = _mm256_set_epi8(1,0,1,0,1,0,1,0,1,0,1,0,...);
  for ( ; i < N - 15; i += 16) {
    __m256i ydata = _mm256_loadu_si256((__m256i *)(IQ + i));
    __m256i ycode = _mm256_loadu_si256((__m256i *)(code + i));
    __m256i ycorr = _mm256_sign_epi8(ydata, ycode);
    ysumI = _mm256_add_epi16(ysumI, _mm256_maddubs_epi16(yextI, ycorr));
    ysumQ = _mm256_add_epi16(ysumQ, _mm256_maddubs_epi16(yextQ, ycorr));
    if (i % (16 * 256) == 0) { // to avoid overflow
      sum_s16(ysumI, (*c)[0])  // c.real += sum(ysumI), ysumI = 0
      sum_s16(ysumQ, (*c)[1])  // c.imag += sum(ysumQ), ysumQ = 0
    }
  }
  sum_s16(ysumI, (*c)[0]) // c.real += sum(ysumI)
  sum_s16(ysumQ, (*c)[1]) // c.imag += sum(ysumQ)
  for ( ; i < N; i++) {
    (*c)[0] += IQ[i].I * code[i].I;
    (*c)[1] += IQ[i].Q * code[i].Q;
  }
  (*c)[0] *= s * SDR_CSCALE; // correlation I
  (*c)[1] *= s * SDR_CSCALE; // correlation Q
}
```



_mm256_*(): AVX2 Intrinsics [1]

[1] https://www.intel.com/content/www/us/en/docs/intrinsics-guide/index.html

Optimization (4/4)

Single Thread Execution Time of API Functions (μs)

CPU/OS = AMD Ryzen AI 9 HX370 (12C/24T), Windows 11

S/W	N =	API Function (sdr_*())		
		mix_carr	corr_std	corr_fft
Pocket SDR ver.0.13, C with AVX2	12,000	1.6	4.8	42.3
	24,000	4.9	6.5	82.6
	48,000	9.7	14.6	85.9
	96,000	16.2	29.4	617.1
Pocket SDR ver.0.13, C w/o AVX2	12,000	4.7	36.2	48.7
	24,000	7.4	73.9	95.9
	48,000	16.9	148.9	107.2
	96,000	33.8	301.3	661.4
Pocket SDR ver.0.11, C with AVX2	12,000	8.0	14.3	63.1
	24,000	17.5	26.7	96.3
	48,000	34.2	55.2	187.7
	96,000	69.6	110.2	641.7
Pocket SDR ver.0.13, python 3	12,000	32.2	48.6	81.1
	24,000	59.6	86.3	169.5
	48,000	116.8	168.4	342.4
	96,000	258.7	330.6	909.7

S/W = Pocket SDR ver.0.13, C with AVX2/NEON

CPU/OS	N =	API Function (sdr_*())		
		mix_carr	corr_std	corr_fft
Intel Core i5-8259U (4C/8T), Ubuntu 22.04 LTS	12,000	5.5	9.1	99.3
	24,000	10.3	17.4	178.8
	48,000	20.5	35.1	251.4
	96,000	41.3	76.5	832.5
M2 Mac mini (Apple M2, 8C/8T), macOS 14.6.1	12,000	5.5	9.3	127.3
	24,000	8.5	18.8	267.7
	48,000	17.1	37.1	461.8
	96,000	36.0	75.6	1161.7
Raspberry Pi 5 (ARM Cortex-A76, 4C/4T), Raspberry Pi OS	12,000	16.1	27.1	319.0
	24,000	32.1	54.7	545.6
	48,000	64.2	108.8	894.6
	96,000	129.2	218.1	3582.6
Raspberry Pi 4 (ARM Cortex-A72, 4C/4T), Raspberry Pi OS	12,000	24.7	49.5	759.3
	24,000	49.5	89.1	1435.4
	48,000	98.8	177.5	3373.6
	96,000	197.6	357.2	11343.5

mix_carr: IF carrier mixing, corr_std: Standard (N+E+P+L) correlator with IF carrier mixing, corr_fft : parallel correlator by FFT, FFT performance optimized by FFTW wisdom at N = 48000

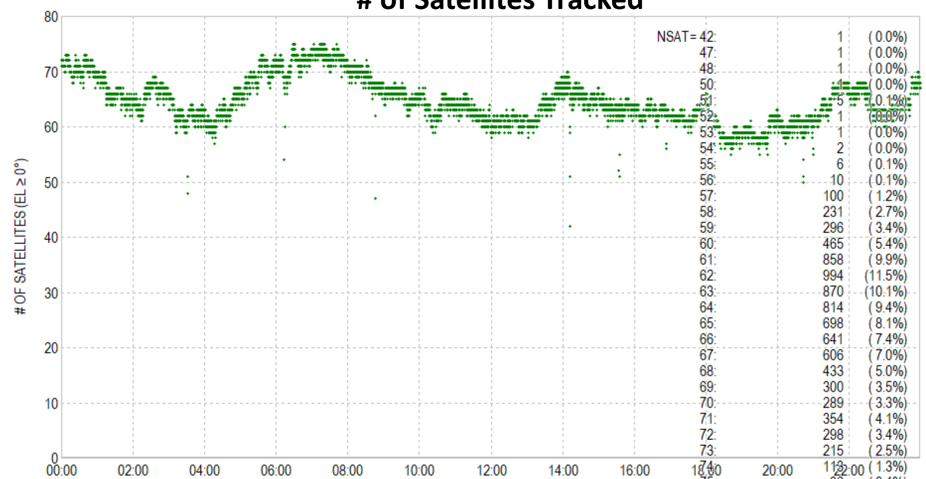
Pocket SDR Performance (1/5)

Pocket SDR ver.0.14

Signals Tracked (RINEX)

```
G   20 C1C L1C D1C S1C C1L L1L D1L S1L C2S L2S D2S S2S C5I
       L5I D5I S5I C5Q L5Q D5Q S5Q
R   20 C1C L1C D1C S1C C4A L4A D4A S4A C2C L2C D2C S2C C3I
       L3I D3I S3I C3Q L3Q D3Q S3Q
E   32 C1C L1C D1C S1C C1B L1B D1B S1B C7I L7I D7I S7I C7Q
       L7Q D7Q S7Q C5I L5I D5I S5I C5Q L5Q D5Q S5Q C6B L6B
       D6B S6B C6C L6C D6C S6C
J   44 C1C L1C D1C S1C C1L L1L D1L S1L C1S L1S D1S S1S C1Z
       L1Z D1Z S1Z C2S L2S D2S S2S C5I L5I D5I S5I C5Q L5Q
       D5Q S5Q C5D L5D D5D S5D C5P L5P D5P S5P C6S L6S D6S
       S6S C6E L6E D6E S6E
S    8 C1C L1C D1C S1C C5I L5I D5I S5I
C   32 C2I L2I D2I S2I C1D L1D D1D S1D C1P L1P D1P S1P C7I
       L7I D7I S7I C7D L7D D7D S7D C5D L5D D5D S5D C5P L5P
       D5P S5P C6I L6I D6I S6I
I    4 C5A L5A D5A S5A
```

of Satellites Tracked

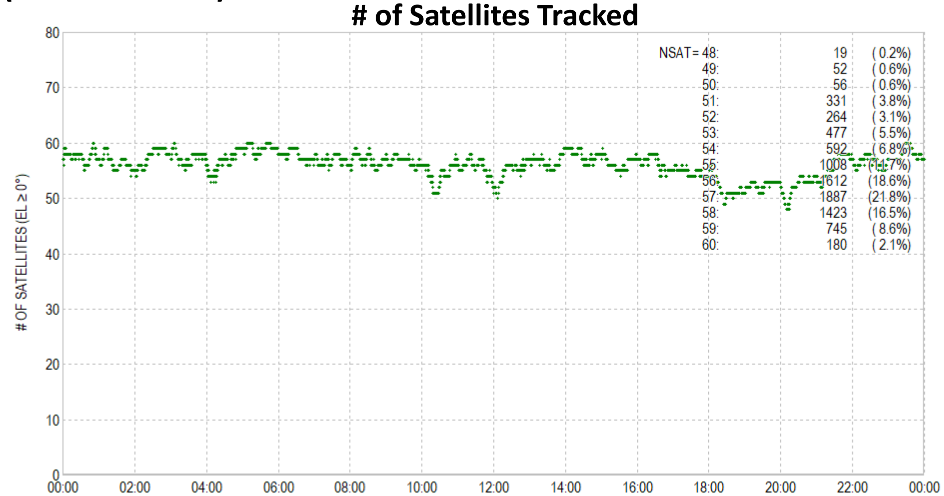


mosaic-X5 (FW 4.14.10.1) *1

Signals Tracked (RINEX)

```
G   20 C1C L1C D1C S1C C1W L1W D1W S1W C2W L2W D2W S2W C2L
       L2L D2L S2L C5Q L5Q D5Q S5Q
R   16 C1C L1C D1C S1C C2P L2P D2P S2P C2C L2C D2C S2C C3Q
       L3Q D3Q S3Q
E   20 C1C L1C D1C S1C C7Q L7Q D7Q S7Q C5Q L5Q D5Q S5Q C6C
       L6C D6C S6C C8Q L8Q D8Q S8Q
J   12 C1C L1C D1C S1C C2L L2L D2L S2L C5Q L5Q D5Q S5Q
C   24 C2I L2I D2I S2I C1P L1P D1P S1P C7I L7I D7I S7I C7D
       L7D D7D S7D C5P L5P D5P S5P C6I L6I D6I S6I
I    4 C5A L5A D5A S5A
```

of Satellites Tracked



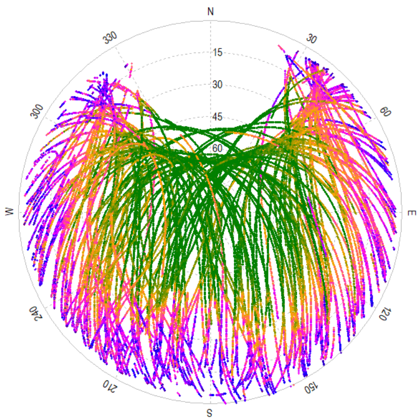
2025-03-08 0:00:00 -23:59:59 GPST, RTCM3: Pocket SDR, SBF: mosaic-X5

*1 SBAS disabled

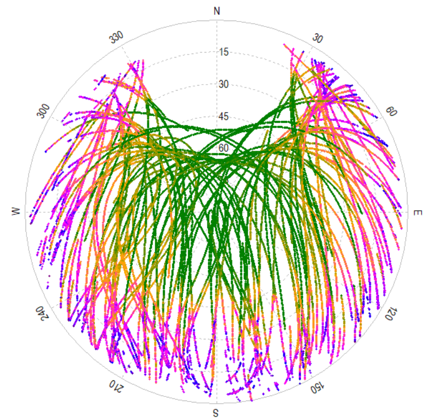
Pocket SDR Performance (2/5)

Pocket SDR ver.0.14

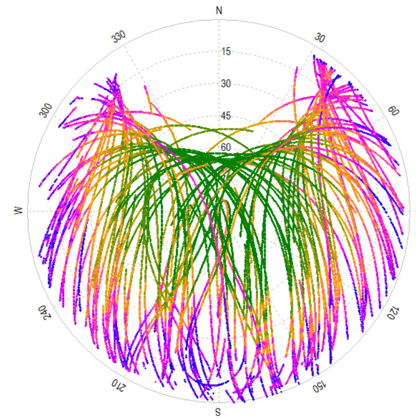
L1/G1/E1/B1



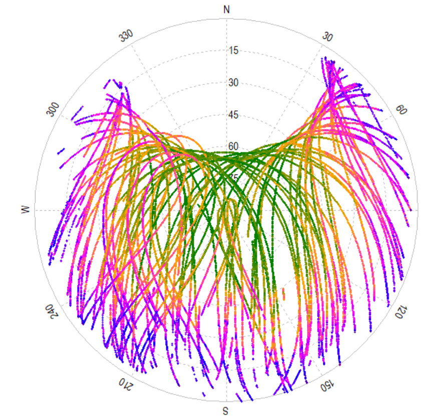
L2/G2/E5b/B2



L5/G3/E5a/B2a

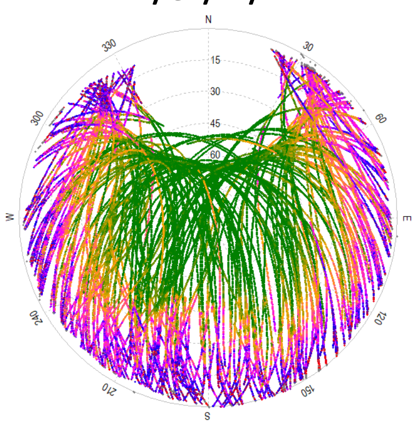


E6/L6/B3

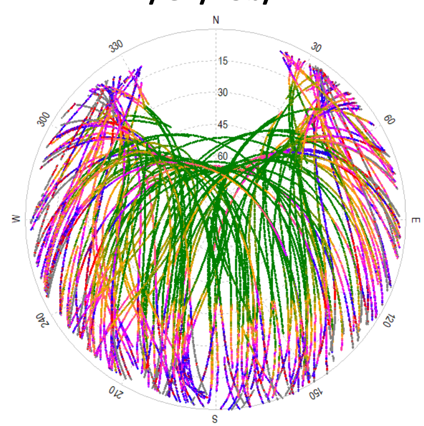


mosaic-X5 (FW 4.14.10.1)

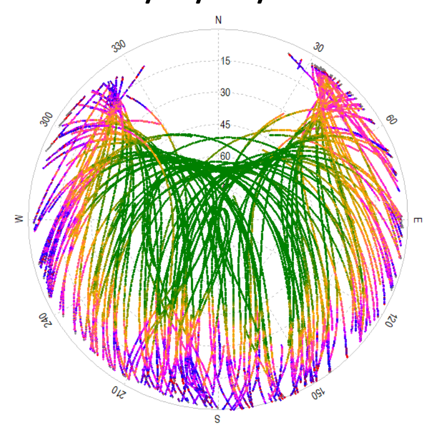
L1/G1/E1/B1



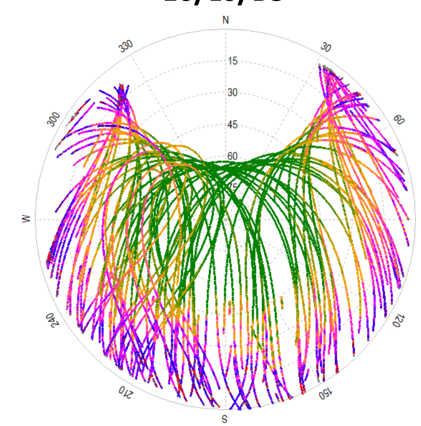
L2/G2/E5b/B2



L5/G3/E5a/B2a



E6/L6/B3



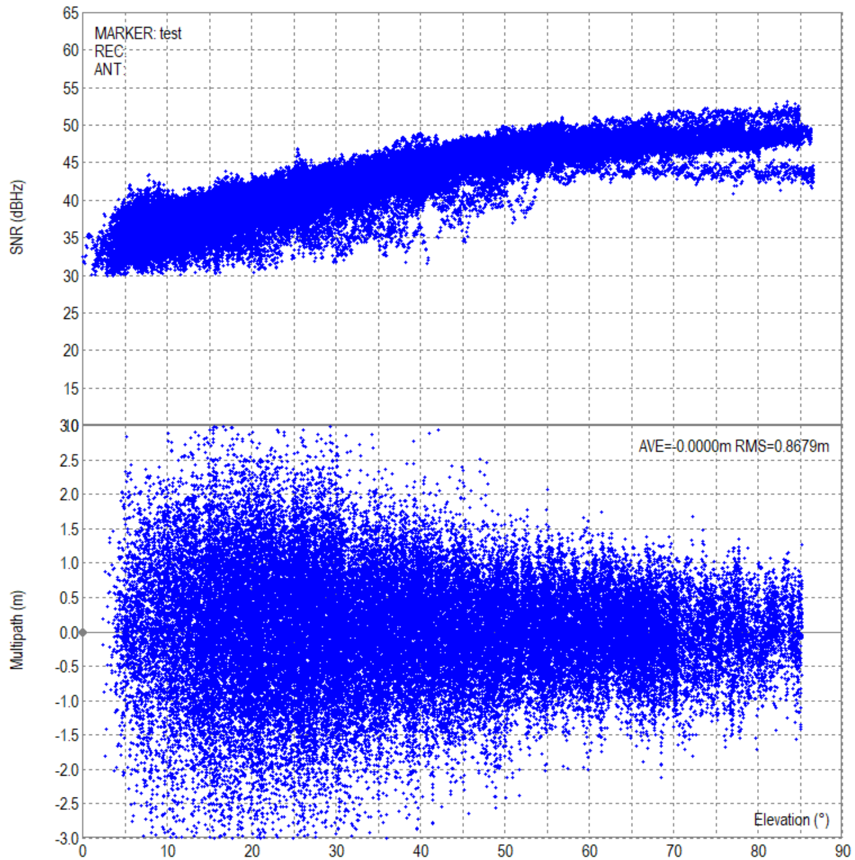
C/N0 =...45...40...35...30...25 <25 (dB-Hz)

2025-03-08 0:00:00 -23:59:59 GPST , RTCM3: Pocket SDR, SBF: mosaic-X5

Pocket SDR Performance (3/5)

Pocket SDR ver.0.14

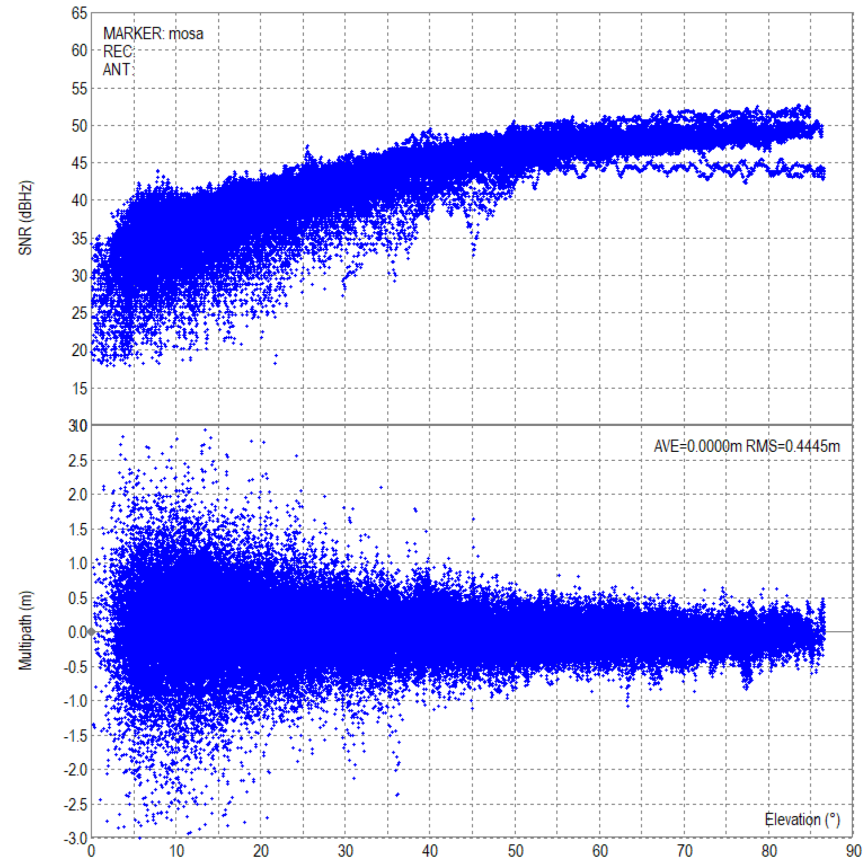
GPS L1C/A C/N0 and MP - Elevation



Correlator spacing = 0.1 chip,
DLL non-coherent integ. time = 20 ms

mosaic-X5 (FW 4.14.10.1)

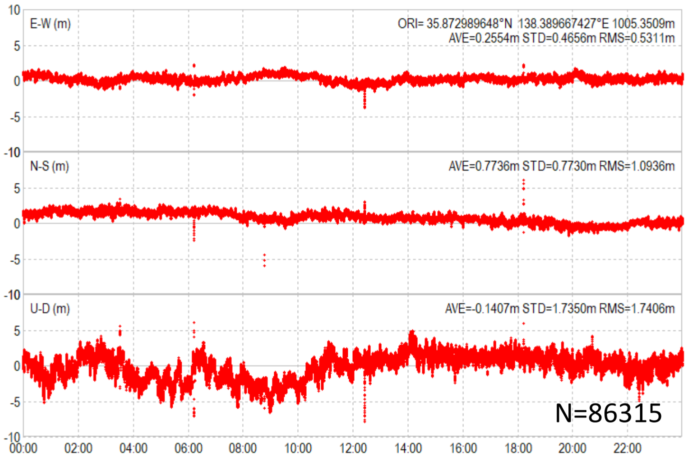
GPS L1C/A C/N0 and MP - Elevation

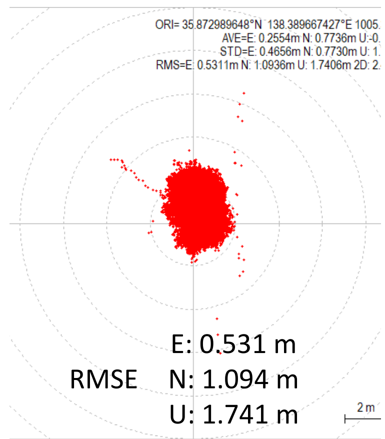


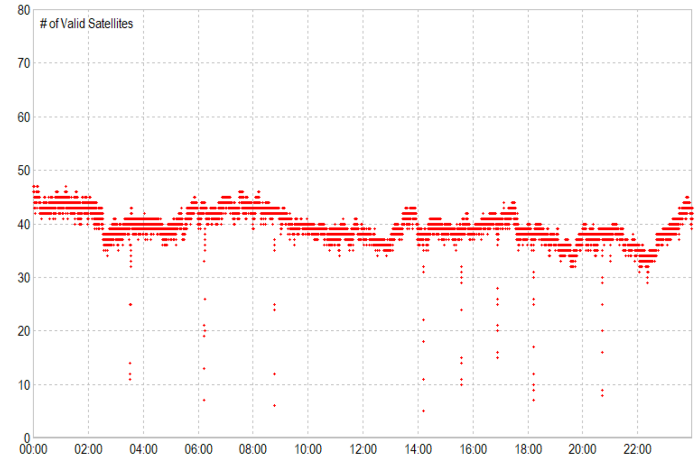
2025-03-08 0:00:00 -23:59:59 GPST, RTCM3: Pocket SDR, SBF: mosaic-X5

Pocket SDR Performance (4/5)

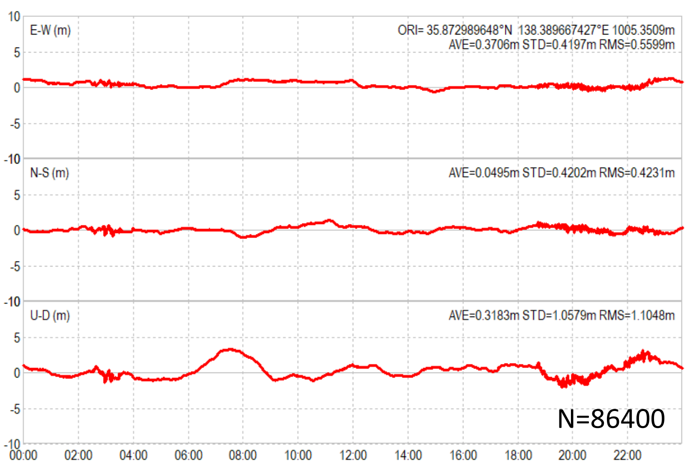
Pocket SDR ver.0.14

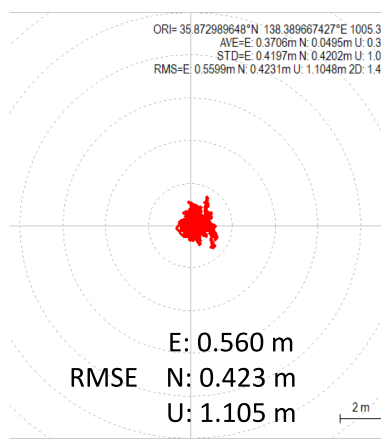


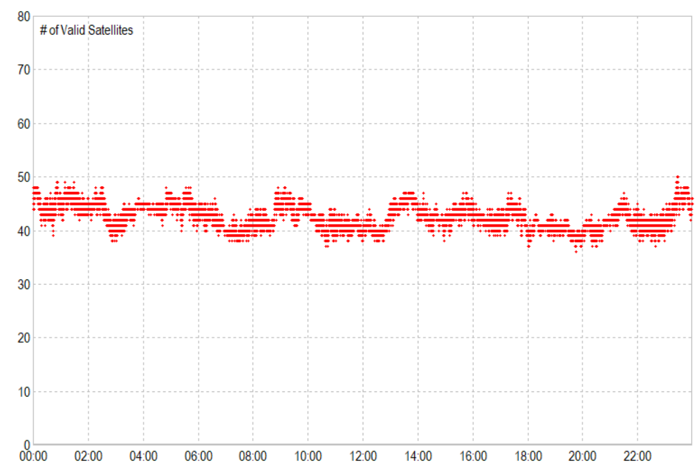




mosaic-X5 (FW 4.14.10.1)



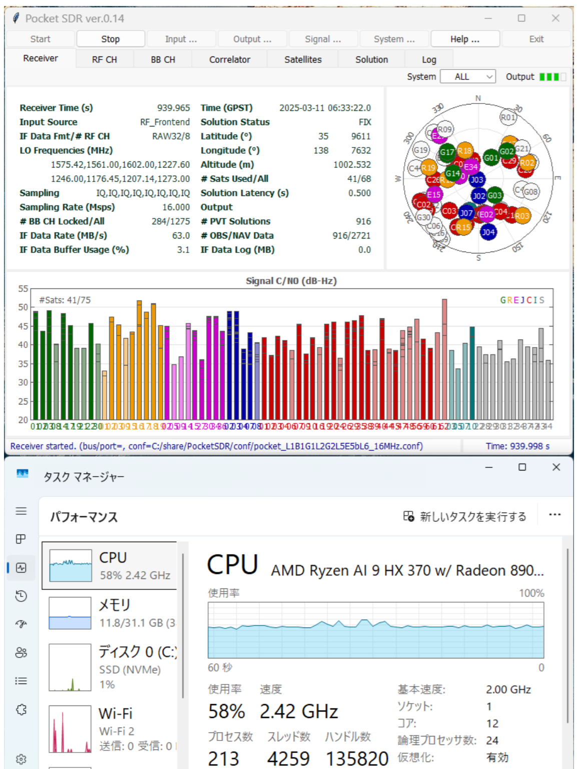




2025-03-08 0:00:00 -23:59:59 GPST, NMEA GGA Solutions, 1 Hz

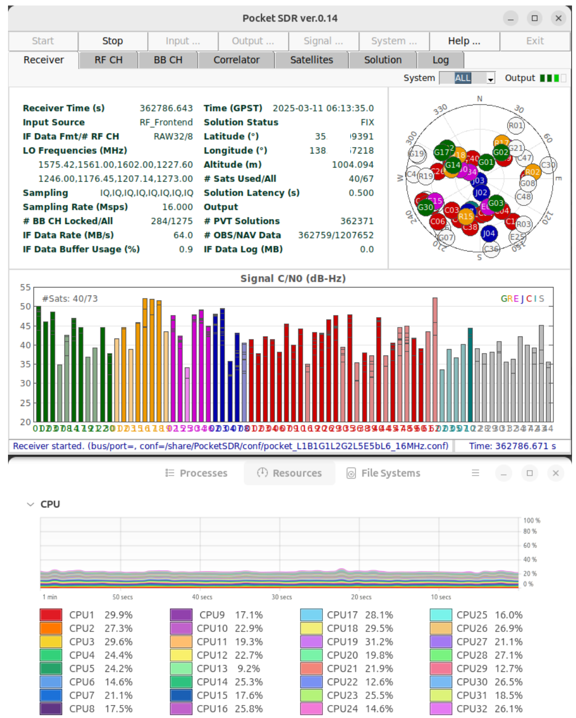
Pocket SDR Performance (5/5)

Laptop Windows PC
CPU Ryzen AI 9 HX370 (12C/24T),
RAM 32GB, SSD 1TB, Windows 11,
Fan mode: standard



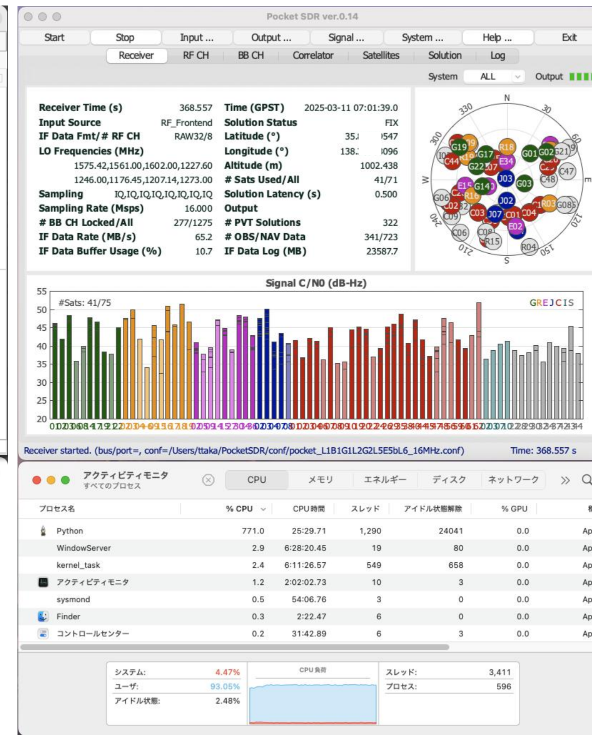
Total CPU Utilization 56-60 %
BB CH Locked/All: 284/1275 (L6D/E: 7CH)

Desktop Linux PC
CPU Ryzen 9 7945HX (16C/32T),
RAM 32GB, SSD 1TB, ubuntu 24.04 LTS,
CPB (core performance boost) disabled



Total CPU Utilization 23-25 %
BB CH Locked/All: 284/1275 (L6D/E: 8CH)

Mac mini
CPU Apple M2 (8C/8T),
RAM 16GB, SSD 512TB,
macOS Sequoia 15.3.1

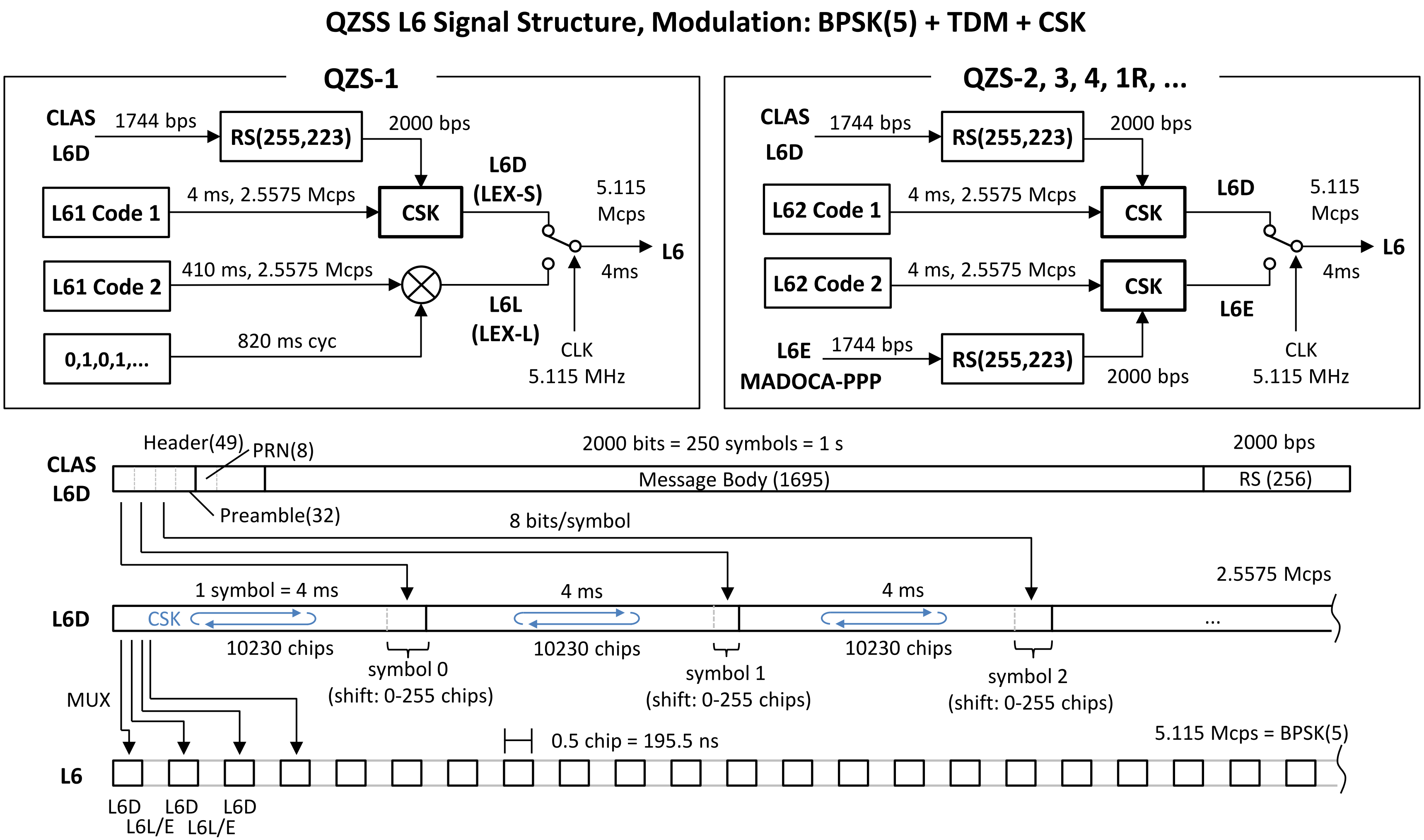


Total CPU Utilization 98-99 %
BB CH Locked/All: 277/1275 (L6D/E: 5CH)

Pocket SDR ver.0.14, FE 8CH, conf=pocket_L1B1G1L2G2L5E5bL6_16MHz.conf

Applications of GNSS SDR

CSK Signal Receiver (1/5)



[1] IS-QZSS-L6-003, Quasi-Zenith Satellite System Interface Specification Centimeter Level Augmentation Service, August 20, 2020

CSK Signal Receiver (2/5)

Commercial Receivers Supporting L6

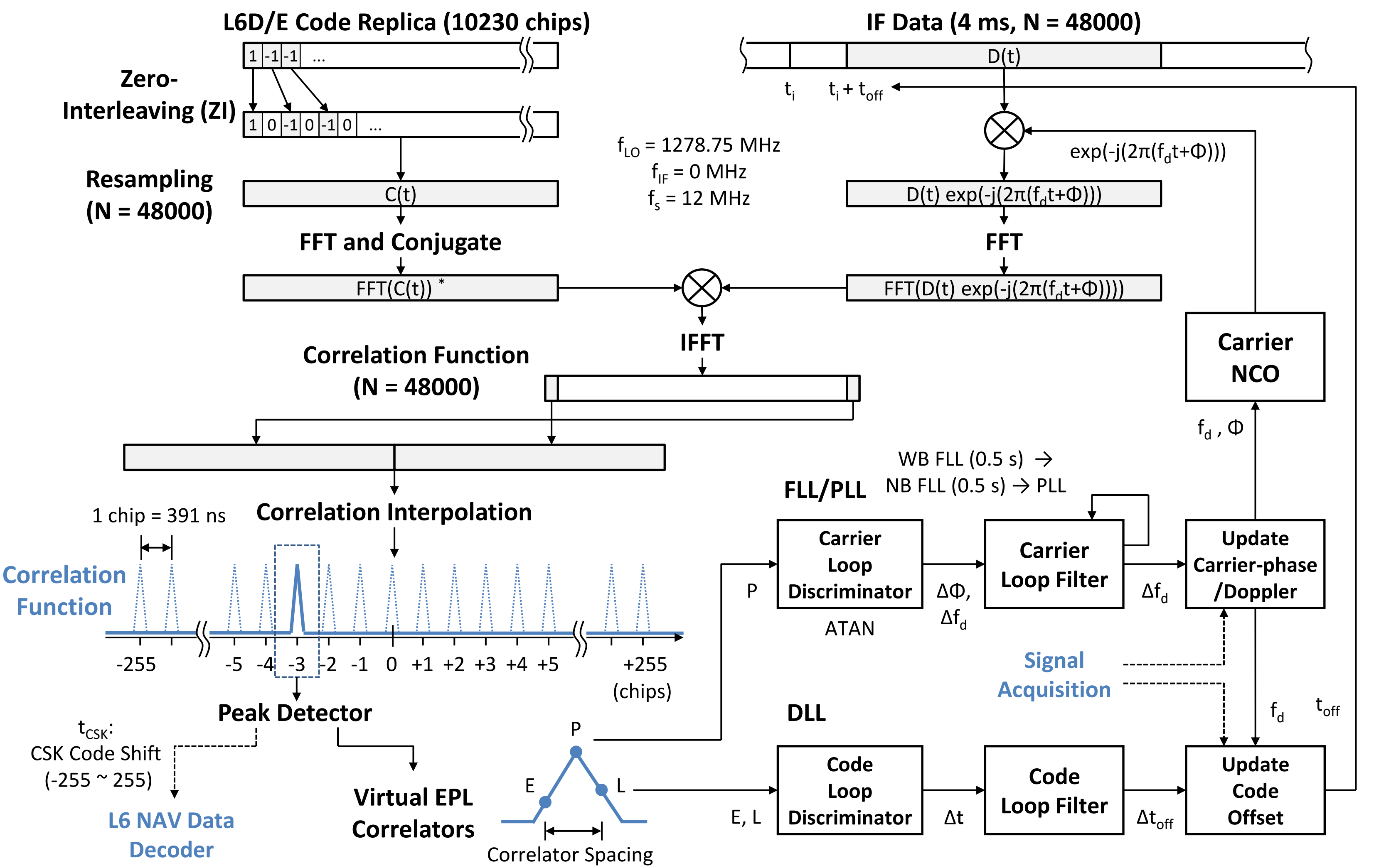
- Trimble : NetR9, Alloy (only track QZS-1 L6, no L6 NAV data)
- NovAtel : OEM7 (only track QZS-1 L6, no L6 NAV data)
- JAVAD : TR-2S/3S, TRE-3S/L (only track QZS-1 L6 ?)
- Septentrio : AsteRx4, AsteRx-m3 CLAS, mosaic-CLAS (only 1CH)
- u-blox : NEO-D9C (no L6 range info, only 2CH), ZED-X20P (?)
- Allystar : HD9310 (no L6 range info, L6D or L6E)
- MSJ, Mitsubishi, Core, LHTC ...

Limitations

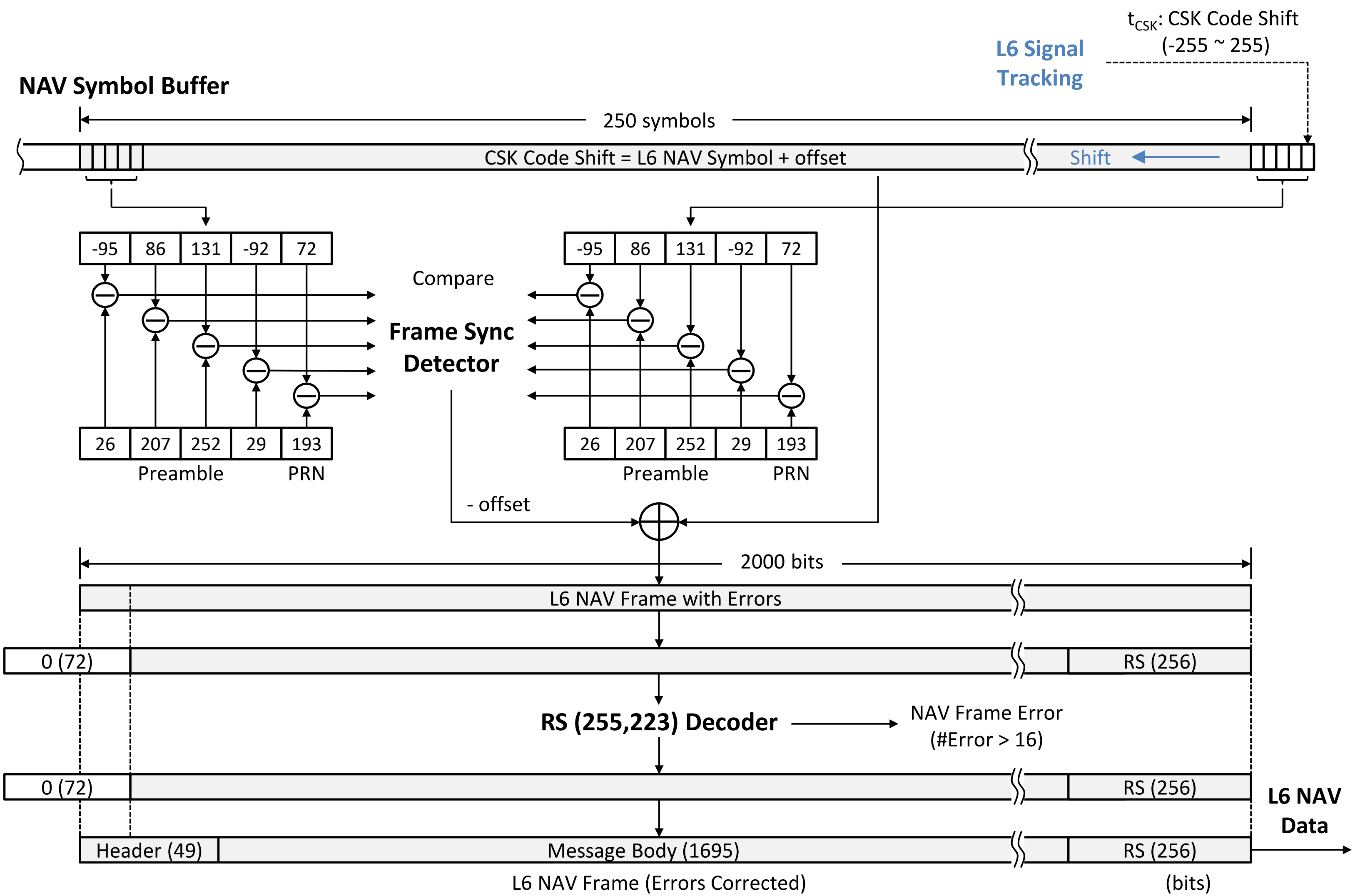
- Tracking L6L (LEX-L) and decoding CSK assisted by L6L as pilot CH [1]
  -> only QZS-1, long acquisition time for L6L
- Decoding CSK assisted by L1C/A or L2C as pilot CH -> needs dual freq. or wide BW RF frontend, needs IFB calibration, long acquisition time for L2C
- No L6 range info of QZS-2 ~ for PVT
- Complicated H/W with many (> 256) correlators to decode CSK

[1] 王 他, QZS-LEX受信機, GPS/GNSSシンポジウム2010, 2010年11月4 ~ 6日, 東京海洋大学越中島

CSK Signal Receiver (3/5)

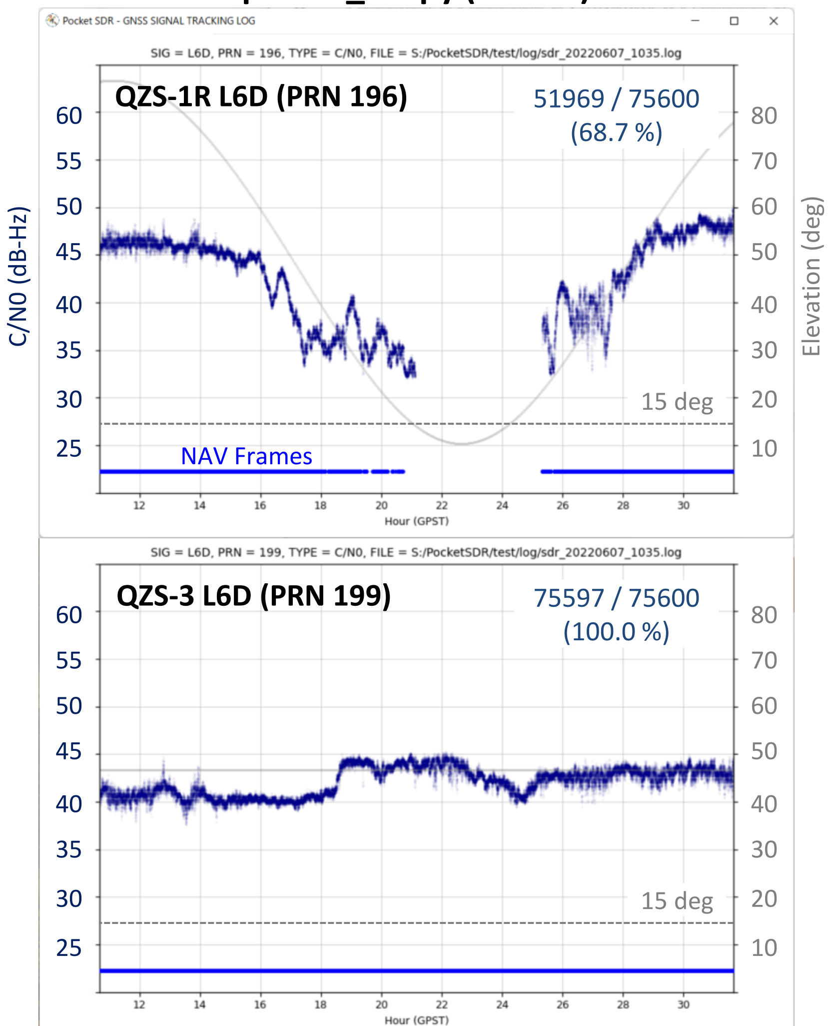


CSK Signal Receiver (4/5)

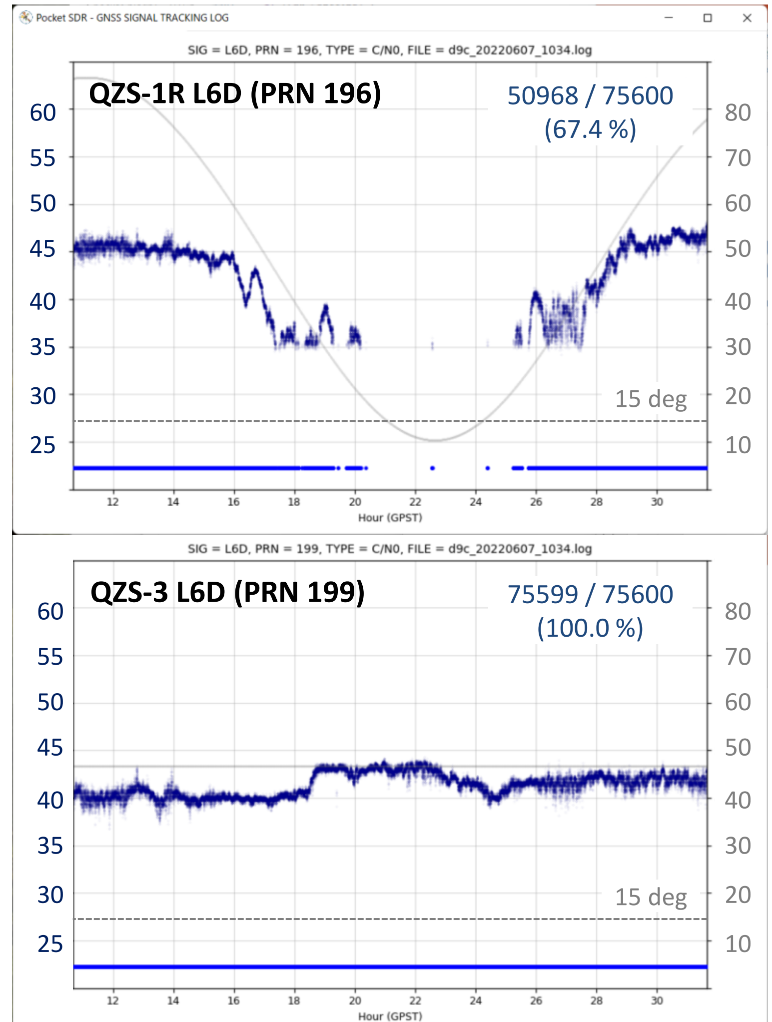


CSK Signal Receiver (5/5)

pocket_trk.py (ver.0.7)



u-blox NEO-D9C

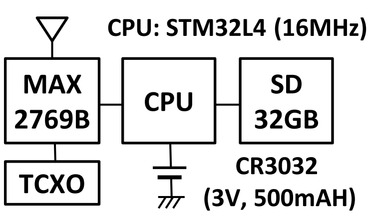


2022-06-07 10:40:00 ~ 2022-06-08 07:39:59 UTC (21 hours)

Snapshot Positioning (1/2)

- **Snapshot Positioning**
  - Record only IF data for < 100 ms
  - PVT by post-processing
  - NAV data provided by external sources
  - Very low power consumption by duty-cycling
  - Fit to cloud-based processing
- **pocket_snap for snapshot positioning**
  - pocket_snap.py (ver. 0.7), pocket_snap (ver. 0.9)
  - L1 band (1575.42 MHz)
  - GPS L1C/A, Galileo E1C, QZSS L1CP, BDS B1CP
  - 4 or 6 Msps x I/Q x 2bits x 8 ~ 20 ms DIF
  - Input RINEX NAV for Ephemerides

Snapshot Receiver Example

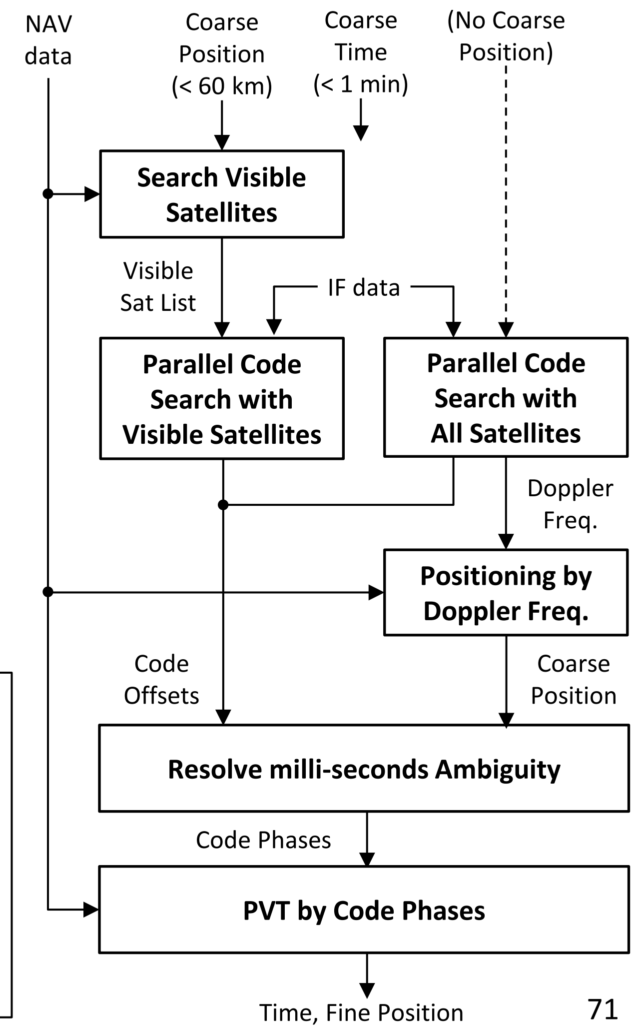


6 Msps x I/Q x 2 bits x 20 ms = 60 kB / snapshot
60 kB x every 1 min x 370 days = 32 GB

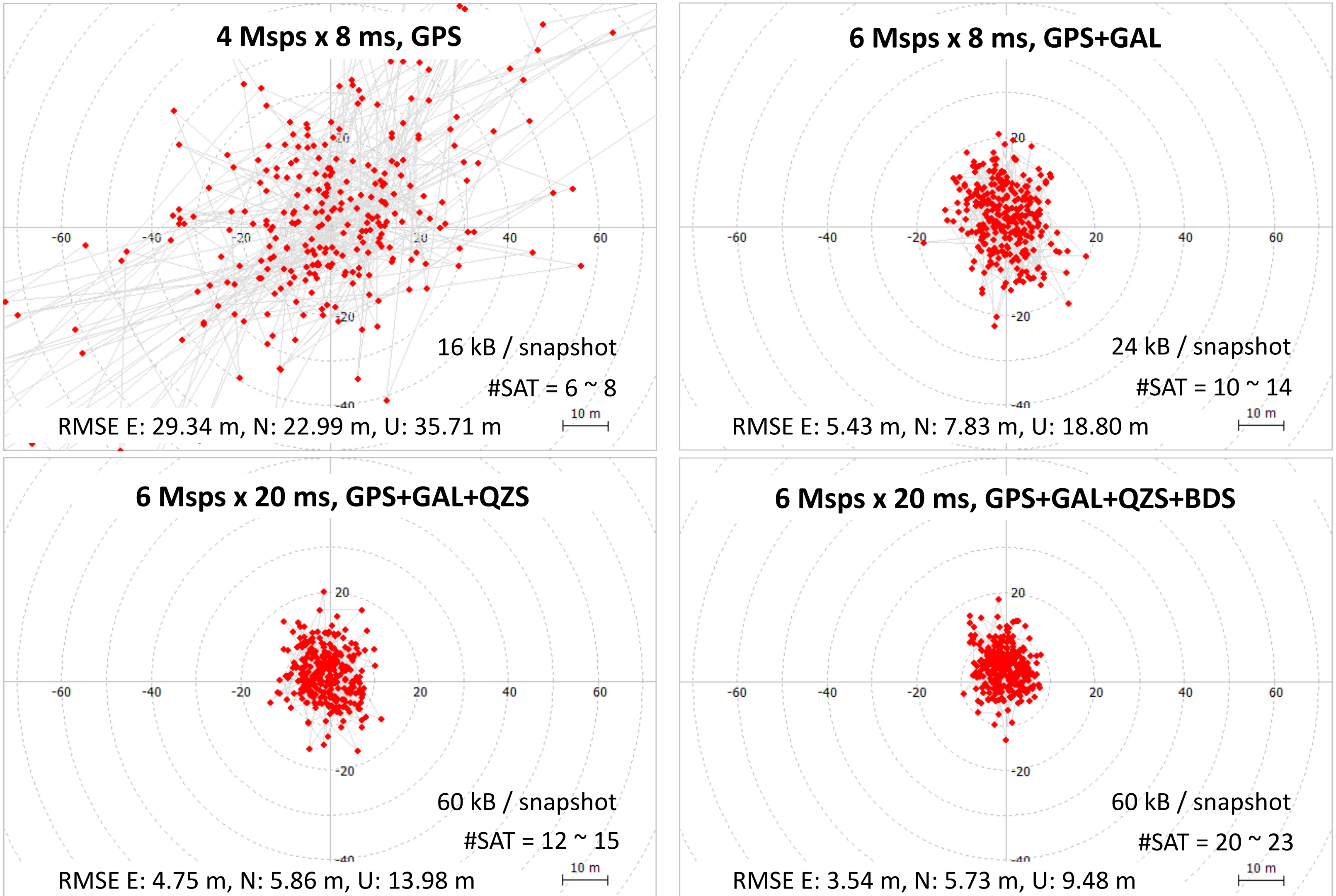
Power Budget

MAX2769B	: 20 mA x 25 ms
STM32L4	: 0.5 mA x 105 ms
TCXO	: 1.5 mA x 25 ms
SD-Card	: 30 mA x 80 ms
Subtotal	: 0.0083 mAH / snapshot
Standby	: 0.0002 mAH / H
Total	: 444 mAH / (1440 x 370)

Snapshot Positioning Flow



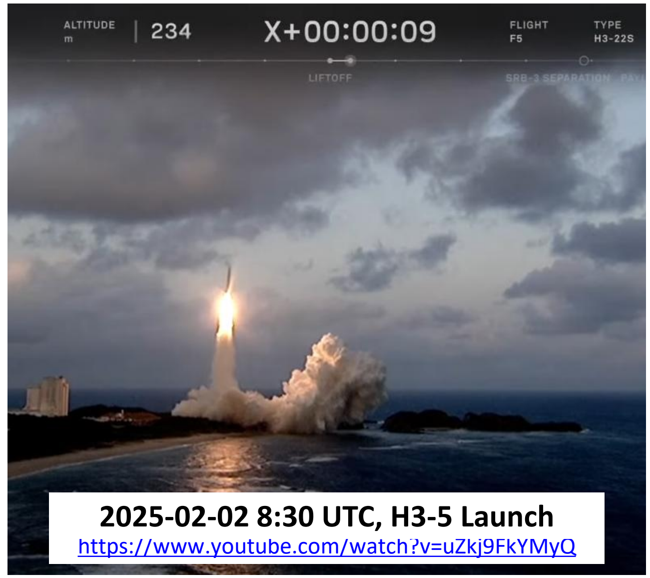
Snapshot Positioning (2/2)



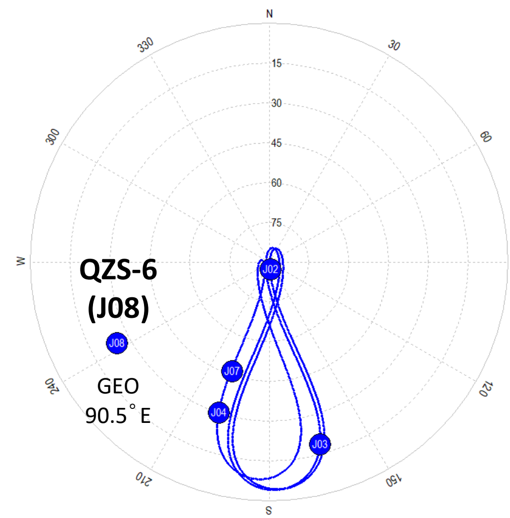
Horizontal Scatter Plots of 300 Snapshots, Post-processed by pocket_snap.py

QZS-6 First Light (1/4)

QZS-6
https://www.satnavi.jaxa.jp/ja/news/2024/11/29/10344/



2025-02-02 8:30 UTC, H3-5 Launch
https://www.youtube.com/watch?v=uZkj9FkYMyQ

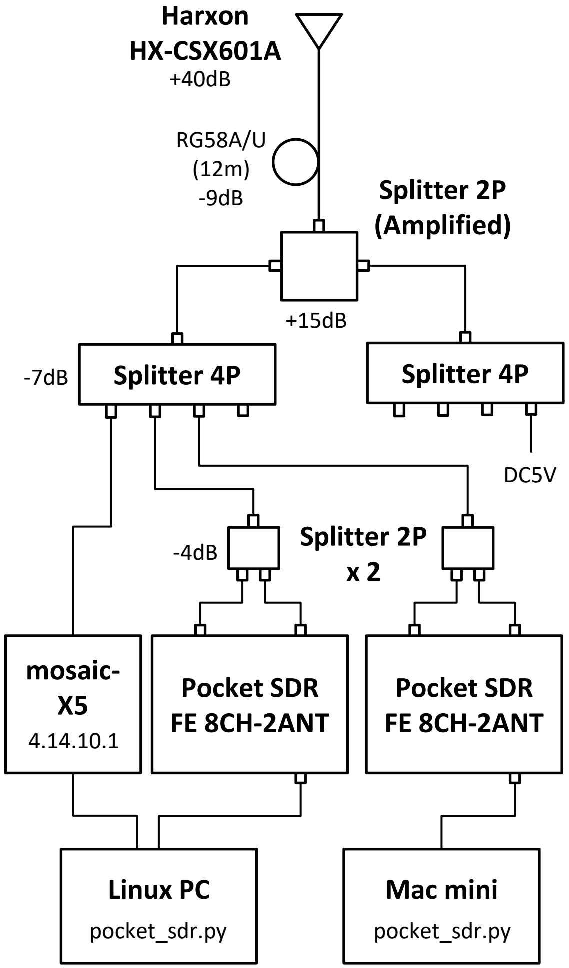


2025-03-05 00:00 UTC, Yamanashi, Japan

Satellite	Launch	Block	Orbit	SV No	SV ID	RINEX Sat ID	Signal and PRN Number										
							L1C/A	L1C	L1C/B	L1S	L1Sb	L2C	L5	L5S	L5SV	L6D	L6E
QZS-1	2010/9/11	I-Q	QZO	1	1	J01	193	193	-	183	-	193	193	-	-	193	(203)
QZS-2	2017/6/1	II-Q	QZO	2	2	J02	194	194	-	184	-	194	194	184	-	194	204
QZS-3	2017/8/19	II-G	GEO	3	7	J07	199	199	-	189	137	199	199	189	-	199	209
QZS-4	2017/10/9	II-Q	QZO	4	3	J03	195	195	-	185	-	195	195	185	-	195	205
QZS-1R	2021/10/26	IIA-Q	QZO	5	4	J04	196	196	(203)	186	-	196	196	(186)	186	196	206
QZS-5	JFY2025	III-Q	QZO	6	5	J05	(197)	197	204	-	-	-	197	-	-	197	207
QZS-6	2025/2/2	III-G	GEO	7	8	J08	(200)	200	205	-	129	-	200	-	205	200	210
QZS-7	JFY2025	III-G	QGEO	8	9	J09	(201)	201	206	-	-	-	201	-	206	201	211
Non-Standard	-	-	-	-	-	J06	(198)	(198)	(198)	-	-	-	(198)	-	-	(198)	(208)
Non-Standard	-	-	-	-	-	J10	202	202	202	-	-	-	202	-	-	202	212

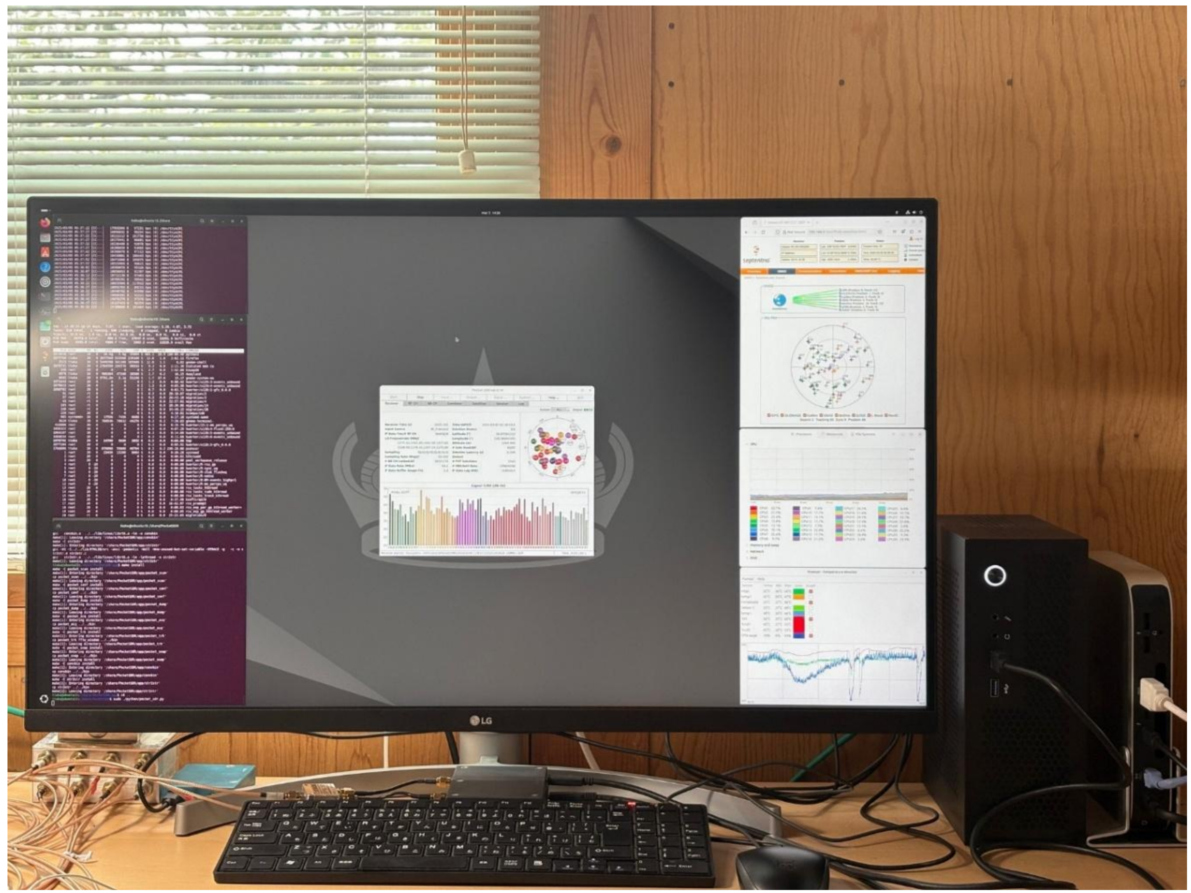
RINEX: RINEX 4.01, L5S: Normal mode, L5SV: Verification mode, (): Assigned but not used

QZS-6 First Light (2/4)



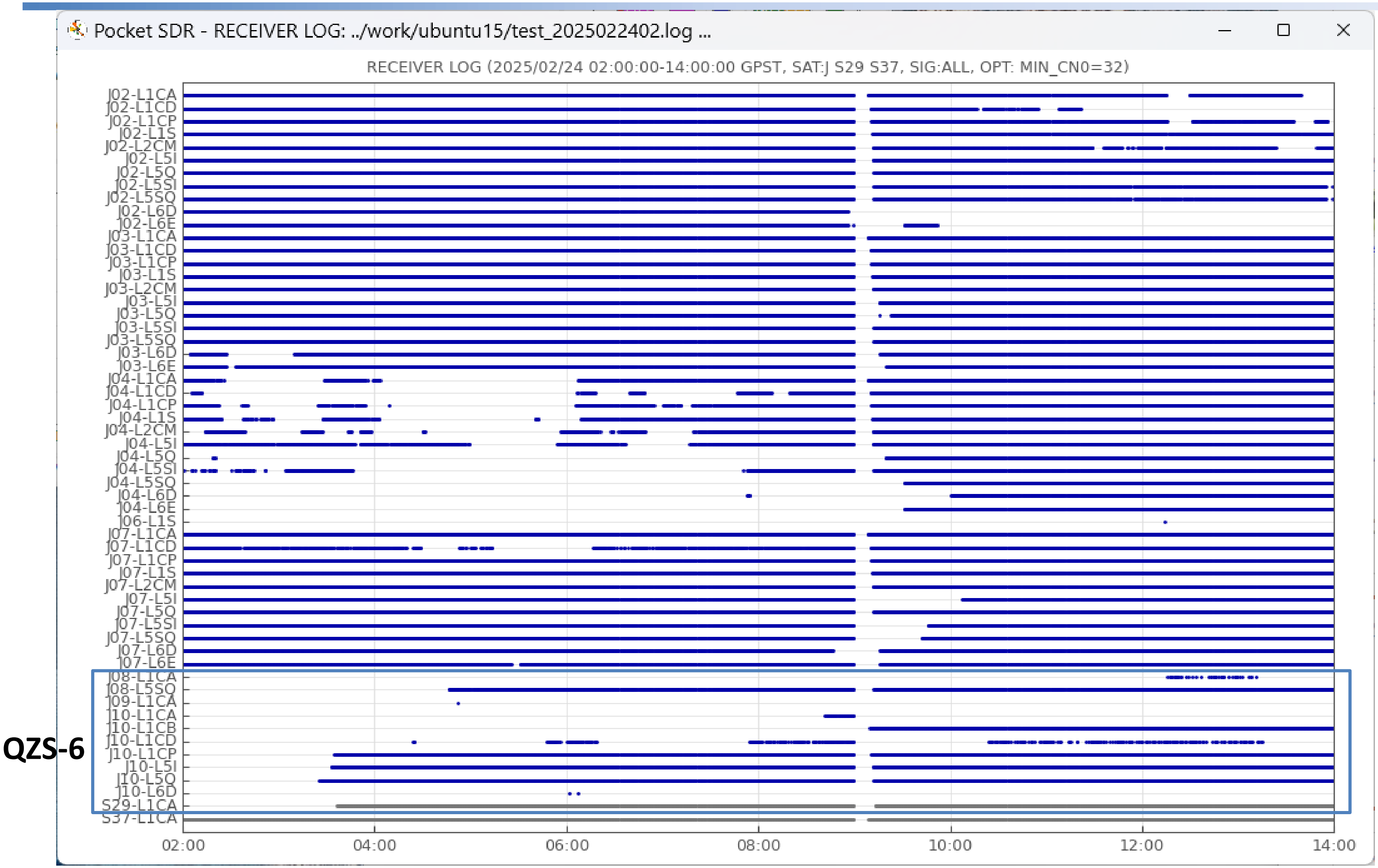
Ryzen 9 7945HX (16C/32T),
RAM 32GB, SSD 1TB,
Ubuntu 24.04 LTS

Apple M2 (8C/8T),
RAM 16GB, SSD 256GB,
macOS 15.3.1



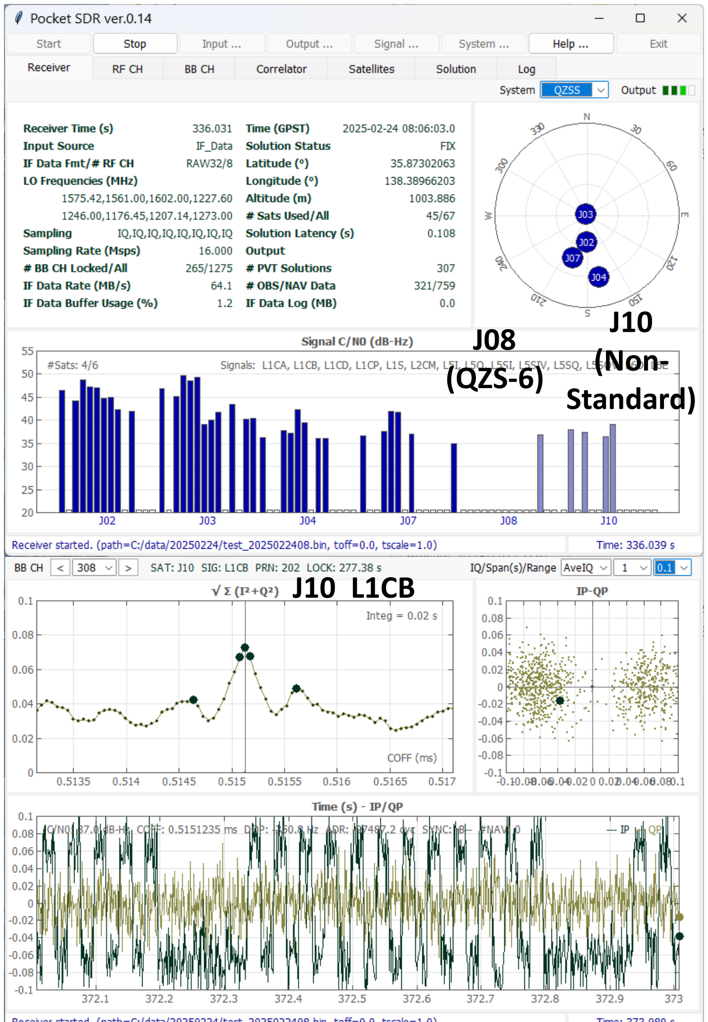
Pocket SDR FE 8CH-2ANT Configuration:
F_S = 16.000 (MHz), F_LO = 1575.42,1561,1602,1227.6,1246,1176.45,1207.14,1273 (MHz)
IQ = 2,2,2,2,2,2,2,2, BW_FILT = 16.4,16.4,8.7,16.4,8.7,16.4,16.4,16.4 (MHz)

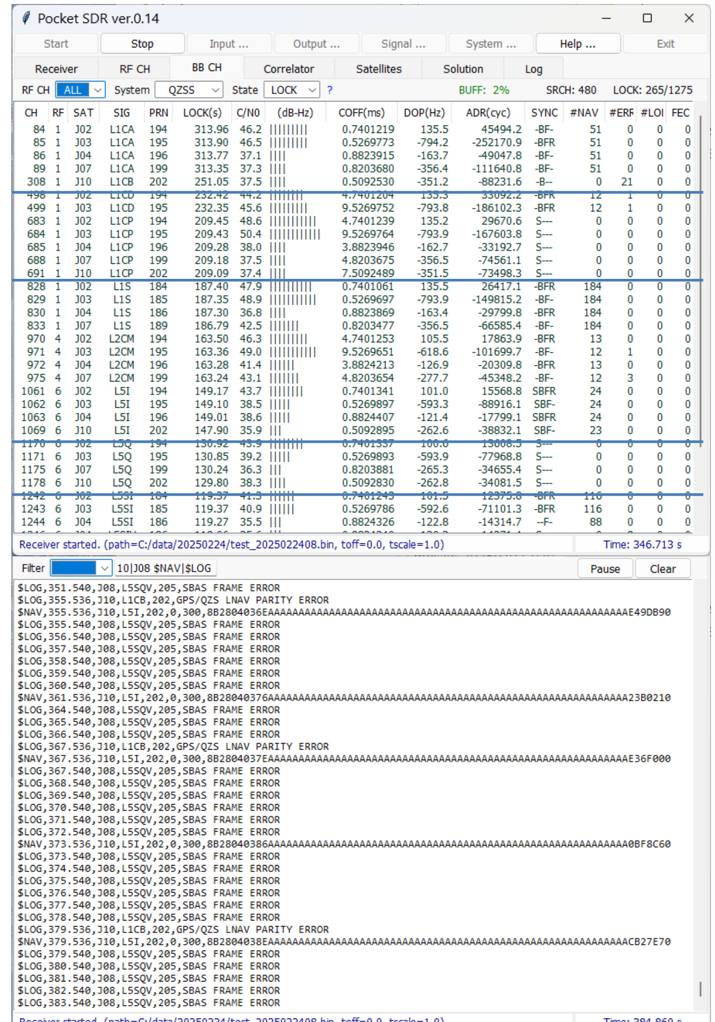
QZS-6 First Light (3/4)



QZS-6 First Light (4/4)

Recorded Raw IF Data (2025-02-24 08:06 - 08:19 GPST, 51.6GB)





J10 PRN202

L1CB

L1CP

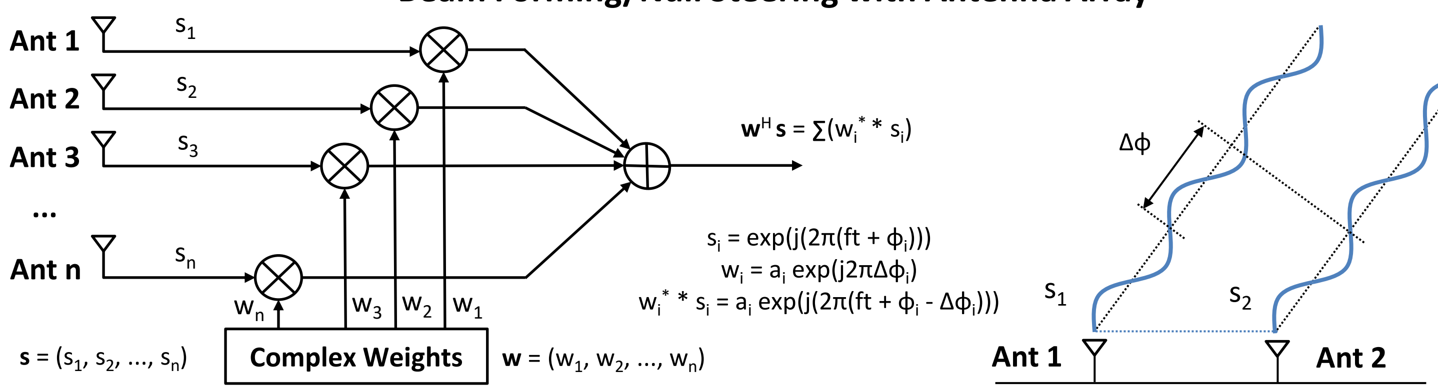
L5I

L5Q

Antenna Array (1/6)

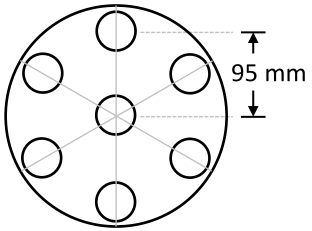
- **CRPA (Controlled Reception Pattern Antenna)**
  - Beam Forming for Multipath Mitigation, Anti-Spoofing, Week Signal Tracking, ...
  - Null Steering for Anti-Jamming, Interference Mitigation, ...
  - PI, MVDR (Capon), STAP, Adaptive Filtering Algorithms (SMI, LMS, RLS), ...
- **DOA Estimation of RF Signals**
  - Radar, Sonar, RF Communication, Radio Astronomy, ...
  - Bartlett Algorithm, MUSIC, ESPRIT, ML, CS, DL, ...
- **Attitude Determination**
  - GNSS 3D-Compass

Beam Forming/Null Steering with Antenna Array

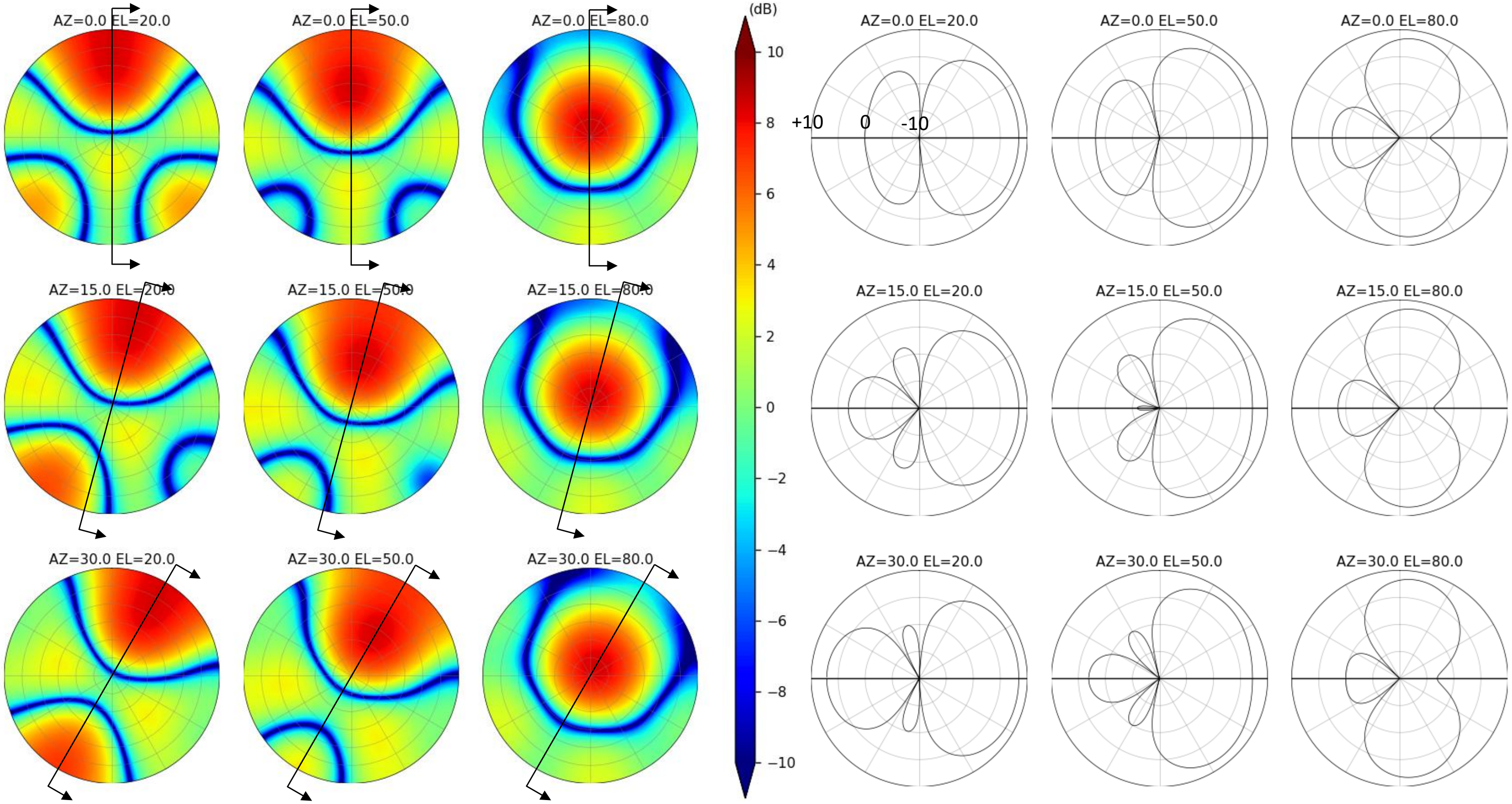


DOA: direction of arrival, PI: Power inversion, MVDR: Minimum variance distortionless response, STAP: Space-time adaptive processing, SMI: Sample matrix inversion, LMS: Least mean squares, RLS: Recursive least squares, MUSIC: Multiple signal classification, ESPRIT: Estimation of signal parameters via rotational invariance techniques, ML: Maximum likelihood, CS: Compressive sensing, DL: Deep leaning

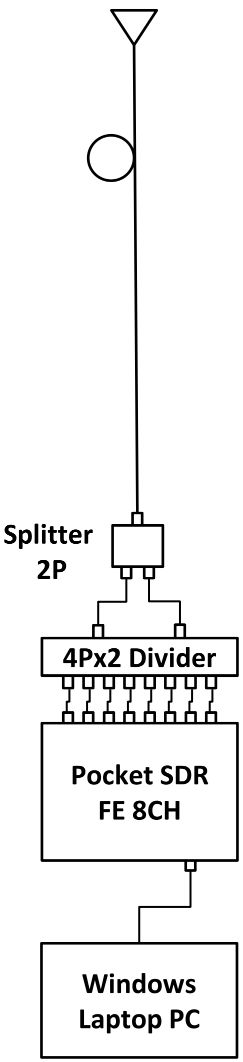
Antenna Array (2/6)

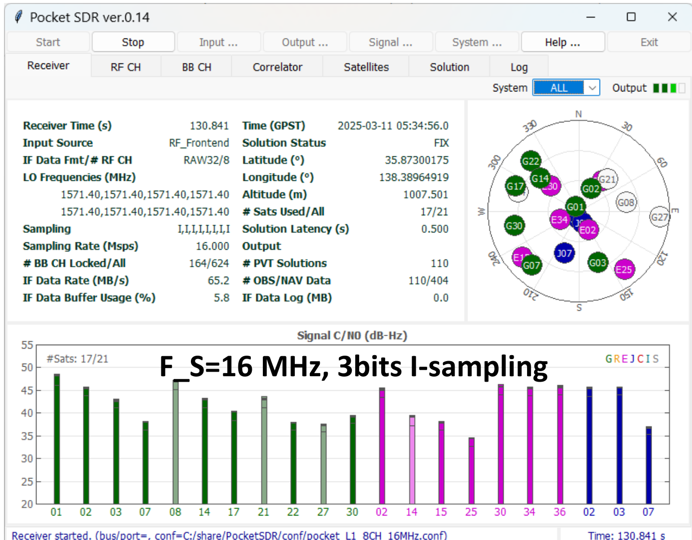


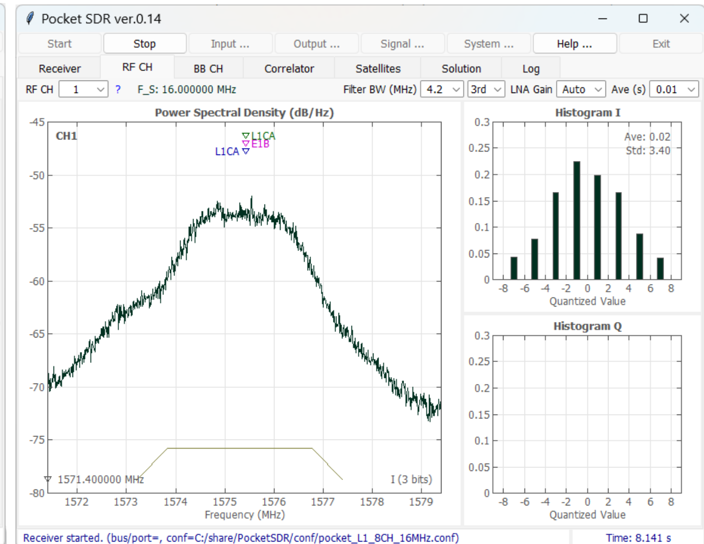
Beam Forming/Null Steering Simulation

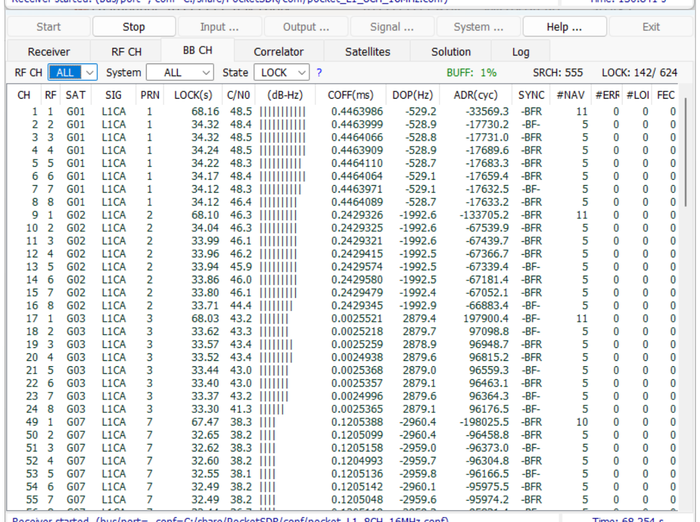


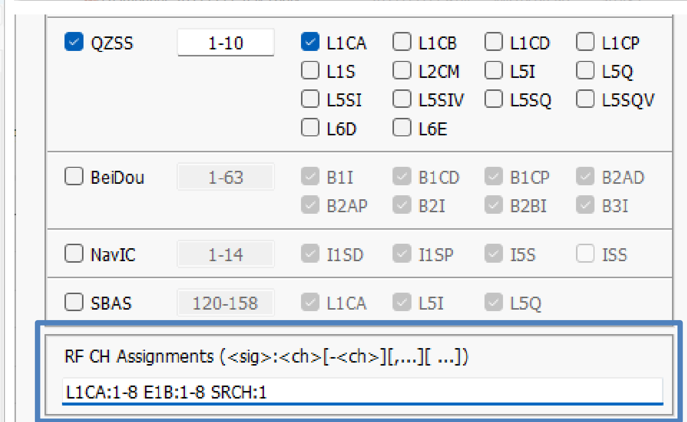
Antenna Array (3/6)







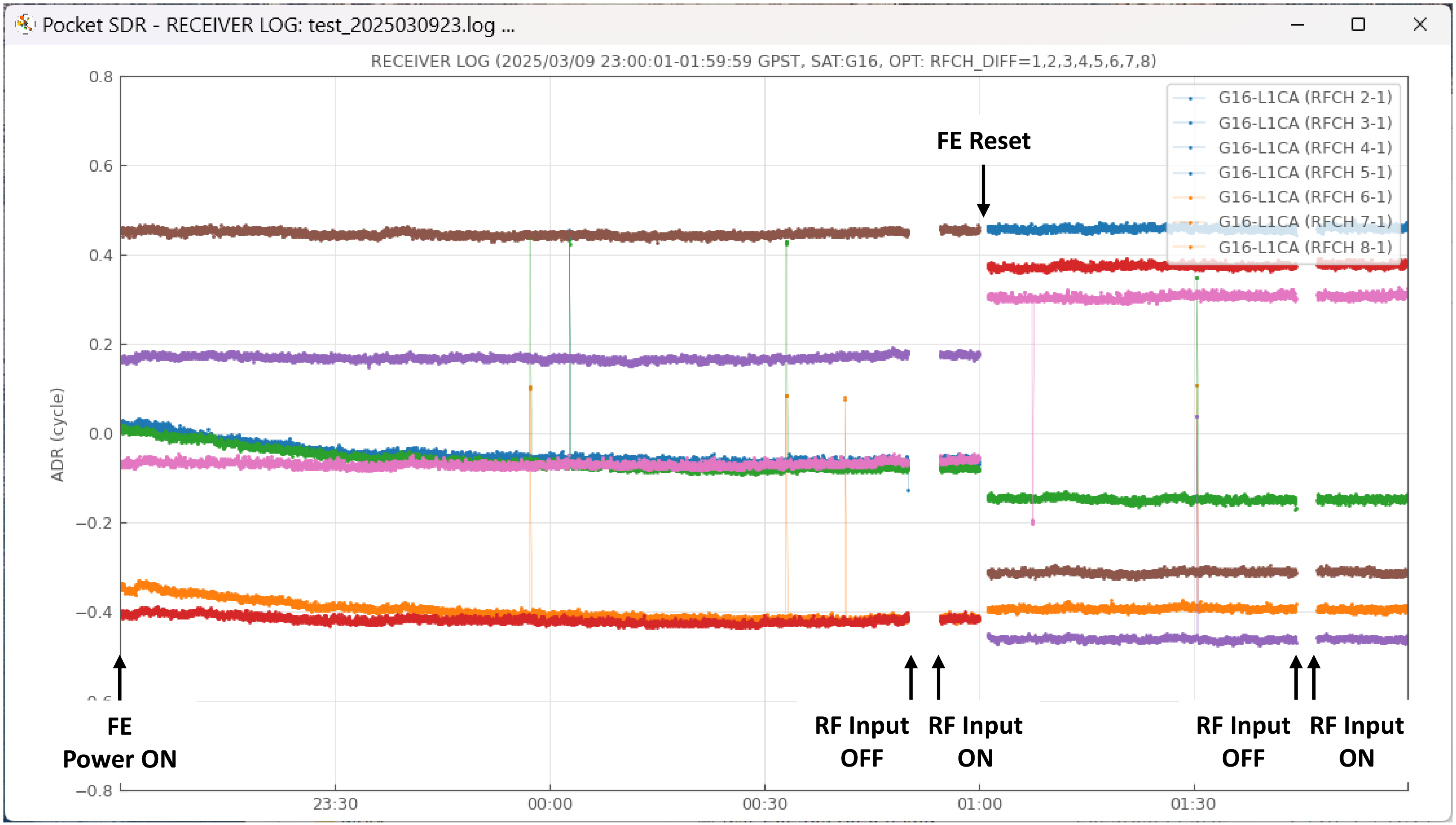




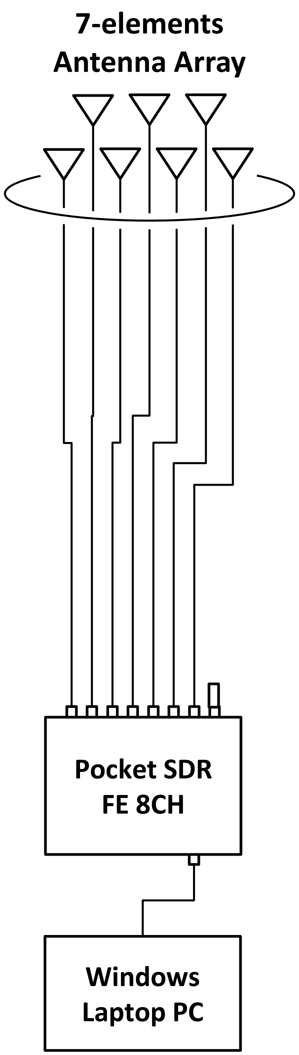
Signal RF CH Assignment Options

Antenna Array (4/6)

Inter-Channel Phase-Bias between RF CHs (SAT=G16, SIG=L1CA)



Antenna Array (5/6)



Antenna Array (6/6)