Global Navigation Satellite Systems – What's Up?

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with support of
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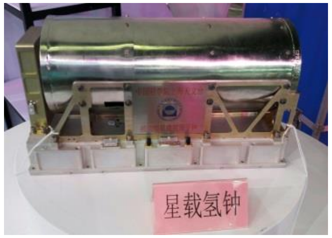
Constellation Status

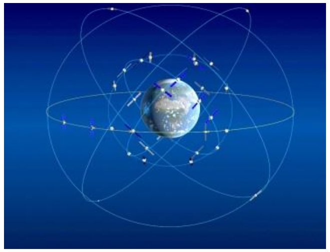
System	Blocks	Signals	Sats*)
GPS	IIA, IIR IIR-M IIF III	L1 C/A, L1/L2 P(Y) +L2C +L5 +L1C	1,11 7 12 (1)
GLONASS	M M+ K1	L1/L2 C/A+P L1/L2 C/A+P, L3 (CDMA) L1/L2 C/A+P, L3 (CDMA)	21+(1) 2 1+(1)
BeiDou	BDS-2 MEO, IGSO, GEO BDS-3S MEO, IGSO BDS-3 MEO, IGSO, GEO	B1-2, B2b, B3 B1, B1-2, B2a/b/ab, B3 B1, B1-2, B2a/b/ab, B3	3, 7, 5 (2), (2) 18, (1), (1)
Galileo	IOV FOC	E1, E6, E5a/b/ab E1, E6, E5a/b/ab	3+(1) 19+(3)
QZSS	Block I Block II IGSO, GEO	L1 C/A, L1C, L2C, L5, SAIF, E6 LEX L1 C/A, L1C, L2C, L5, L1S, E6, L5S	1 2, 1
IRNSS	IGSO, GEO	L5, S	4+(1), 3

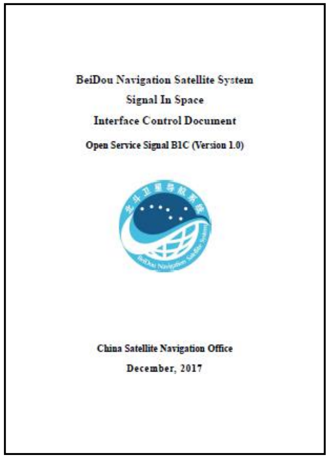
*) Status May 2019; brackets indicate satellites not declared healthy/operational

BeiDou-3

- Five experimental satellites (BDS-3S)
  - launched 2015-2016 (non-operational)
  - technology demonstration (ISL, H-Maser, platforms)
- Global Constellation (BDS-3)
  - 18 operational MEO satellites (launched 2017-2018)
  - 2 platforms (8 x SECM, 10 x CAST)
  - 1 IGSO and 1 GEO in testing
  - Early service declared Dec. 2018
- New Signals
  - B3I declared as open signal, available on BDS-2 and -3
  - New B1C and B2a signal on BDS-3
  - B2b and B2ab transmitted on BDS-3 but no ICD yet
  - New navigation CNAV1 on B1C and CNAV2 on B2a (resembling GPS CNAV2 on L1C and CNAV on L2C/L5)
  - Advanced modulation schemes (QMBOC, ACE-BOC)
  - PRN range extended to 63

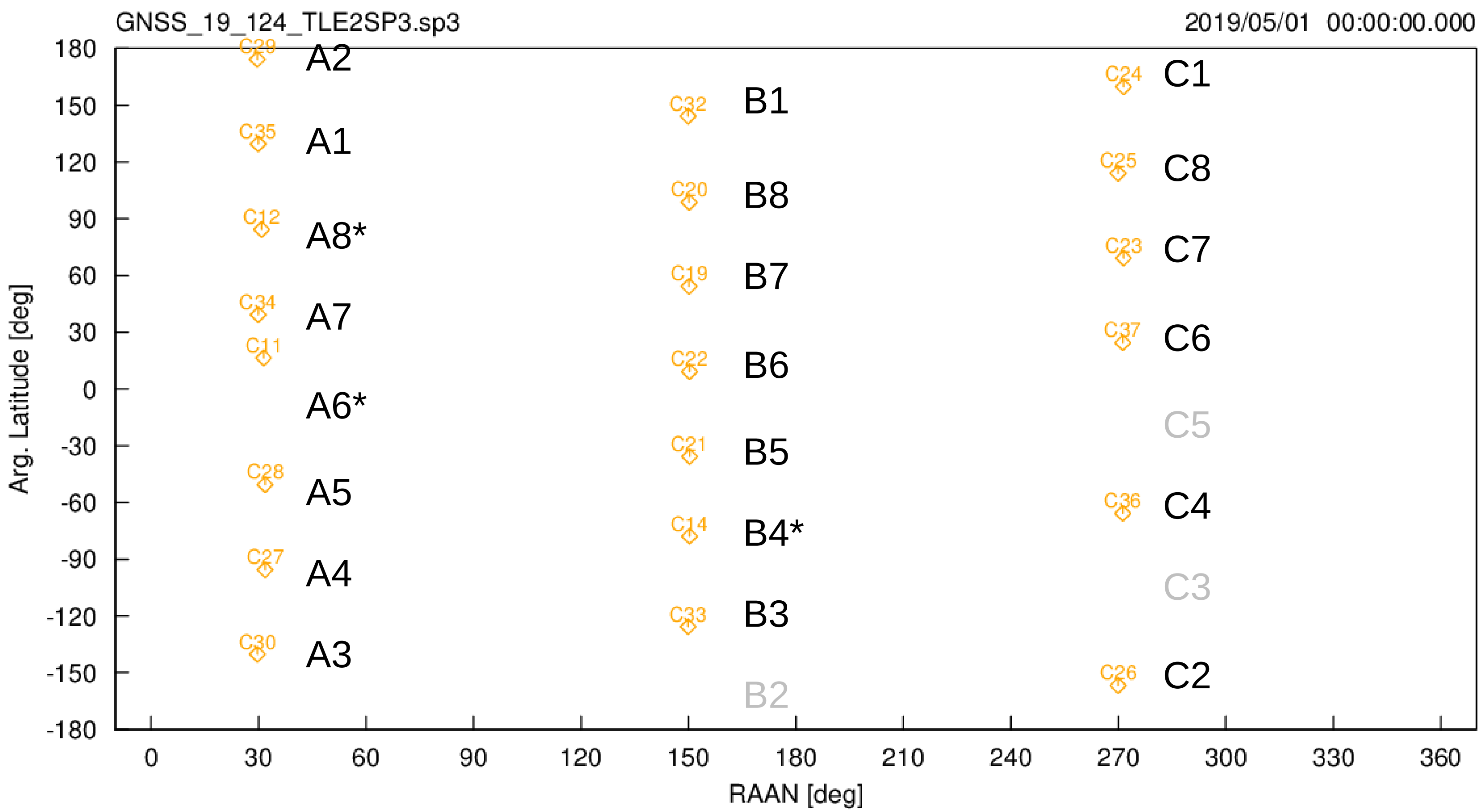





BeiDou Navigation Satellite System
Signal In Space
Interface Control Document
Open Service Signal B1C (Version 1.0)

China Satellite Navigation Office
December, 2017

BeiDou-2/3 MEO Constellation Chart (Walker 24/3/1)



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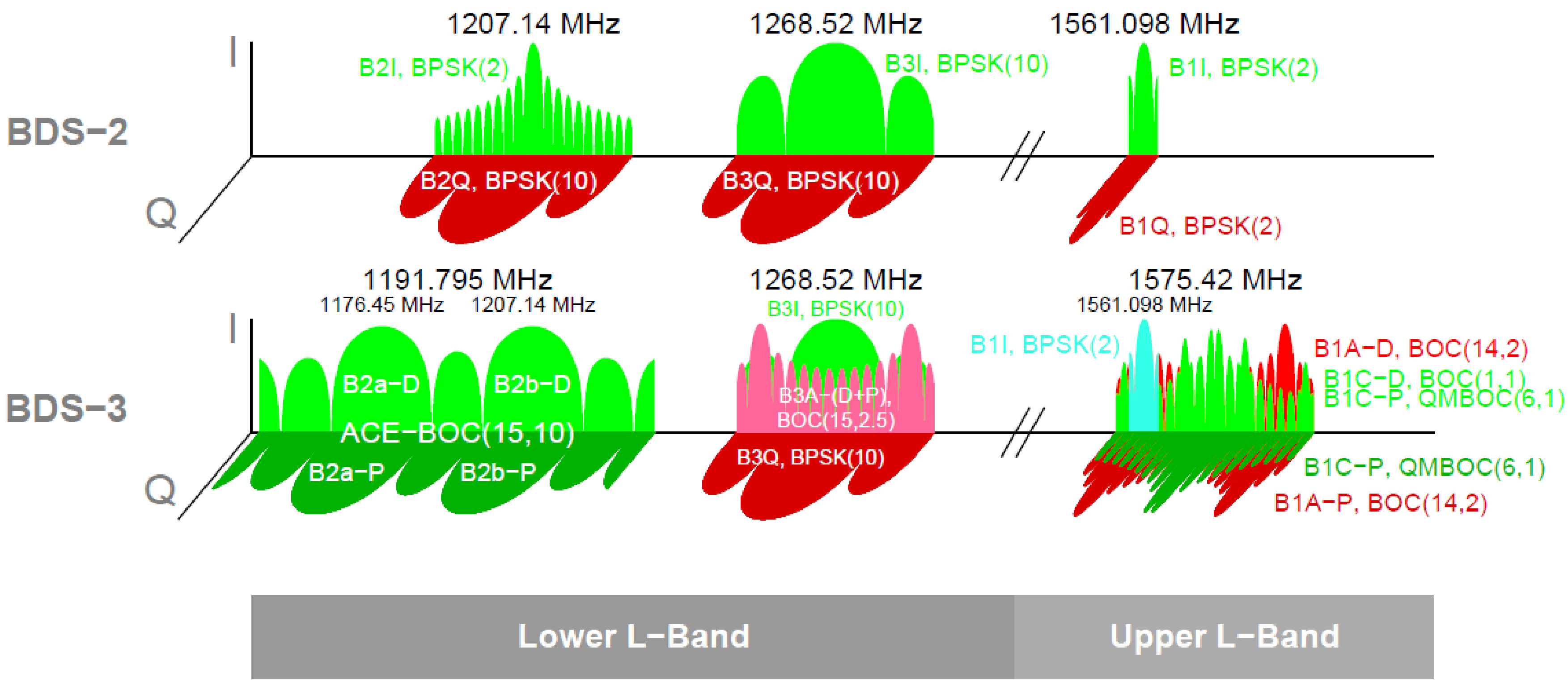
BeiDou Signal Spectrum



- B1I and B3I common to all satellites
- B2I phased out?
- New B1C/B2a signals (interoperable with GPS L1C/L5, Galileo E1/E5a)

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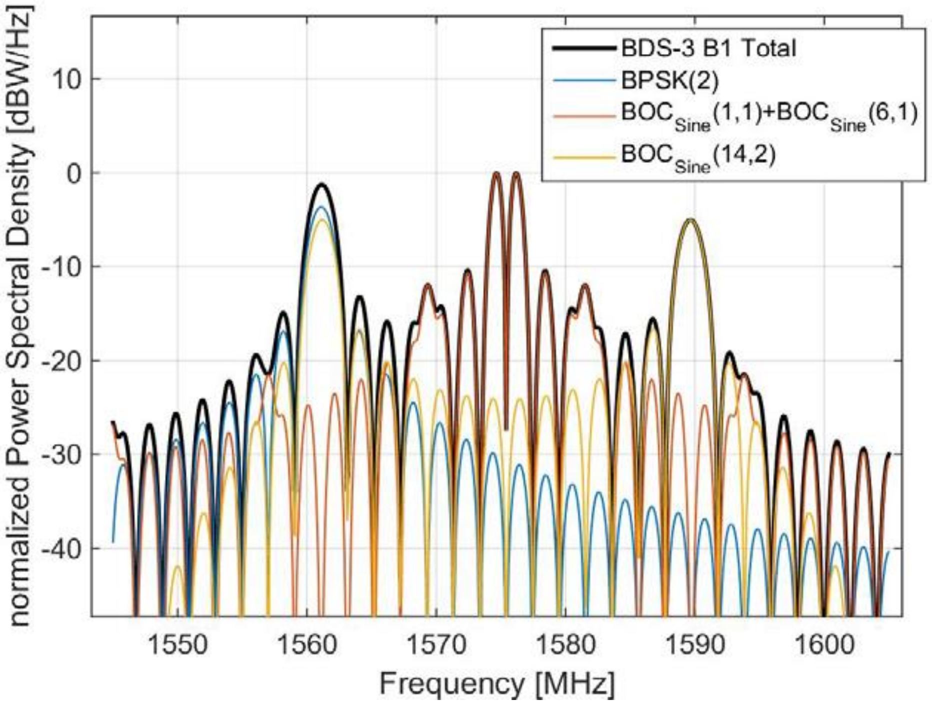
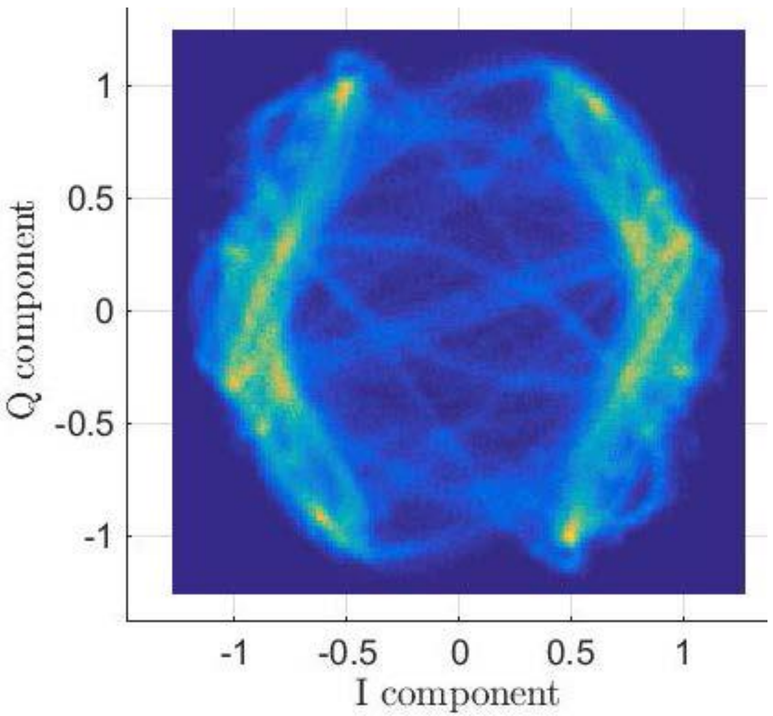
BeiDou-3 Modulation Techniques

- Quadrature Multiplexed BOC modulation (QMBOC) for B1 signal
    - Independent realization of interoperable MBOC signal in L1 band (alternative to Galileo CBOC and GPS TMBOC)
    - Data signal uses BOC(1,1) on I-channel
    - Pilot signal uses superposition of BOC(1,1) (I-channel) and BOC(6,1) (Q-channel)
    - Flexible choice of relative signal powers for all components
- CEM via Intermodulation Construction (CEMIC)
    - Constant envelope modulation for “arbitrary” number of signals, power ratios, and phase relation / frequency (alternative to CASM and POCET)
    - Used to combine 5 (?) signal components plus intermodulation product in B1 band: B1I, B1C-data, B1C-pilot, B1A-data (TBC), B1A-pilot (TBC)
- Asymmetric Constant Envelope Binary Offset Carrier (ACE-BOC)
    - Dual-frequency constant envelope multiplexing technique
    - Similar to Galileo AltBOC, but allows different powers in the two sub-bands (here B2a, B2b)

BeiDou-3 B1 Spectrum and I/Q-Diagram





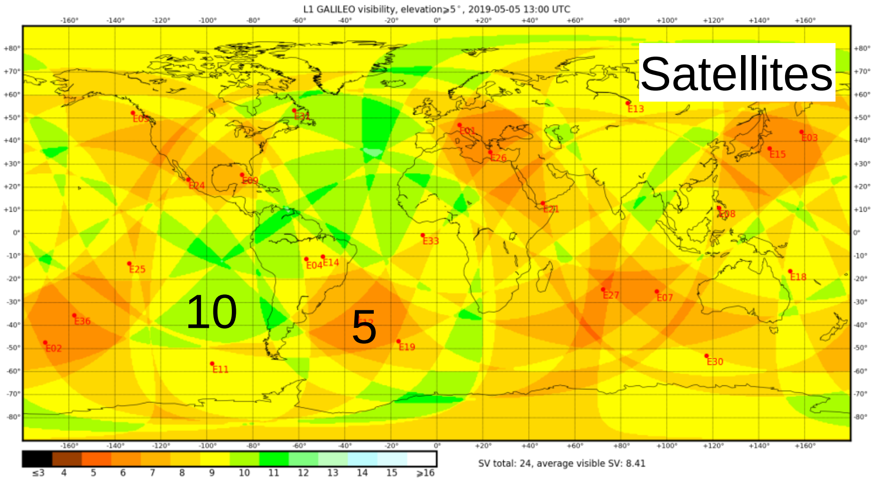
Thoelert S., Antreich F., Enneking Ch., Meurer M., "BeiDou 3 Signal Quality Analysis and its Impact on Users," *Proc. ION ITM 2019*, Reston, Virginia, Jan.2019, pp. 909-924. https://doi.org/10.33012/2019.16738

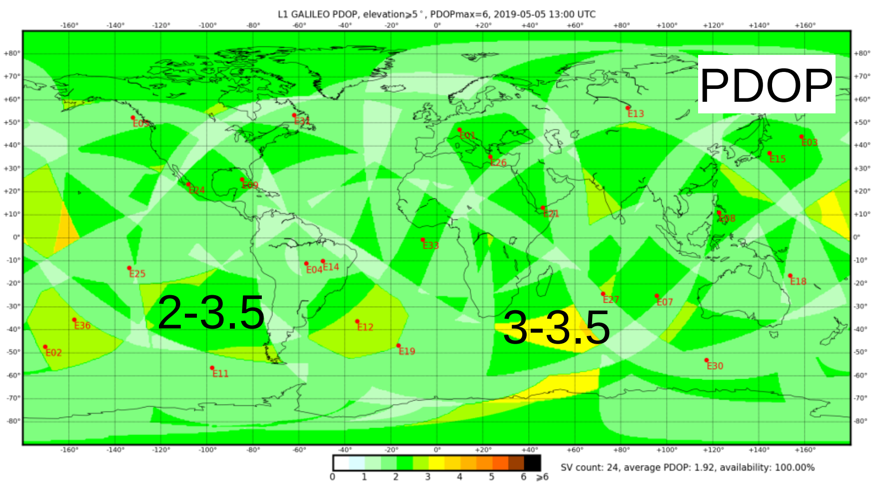
BeiDou-3 Intersatellite Links

- K-band dual one-way ranging
  - Earth oriented phased array antenna, steerable up to 60° off-nadir
  - Time-multiplexed operation using predefined link allocation table
  - One forward and backward ranging measurement per slot (1.5 s each)
  - ~5 cm precision
- Processing
  - Extrapolation of fwd/bkwd ranges to common epoch (coarse a priori orbit)
  - Arithmetic mean of fwd/bkwd one-way range yields geometric range plus delays, difference yields clock offsets plus delays
- Enables orbit determination with regional ground network
  - Measurements not publicly available
  - Published results limited to BDS-3S and partial BDS-3 MEO constellation

Galileo – "Accuracy Matters"

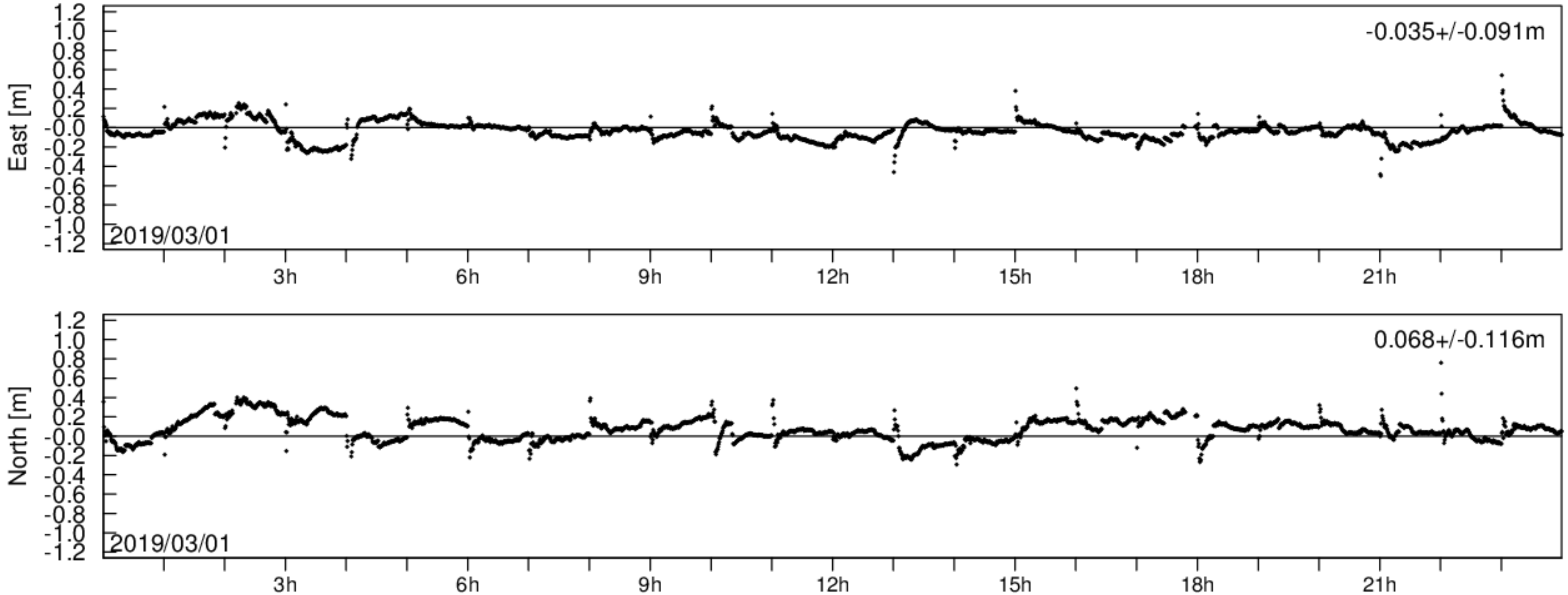
- Now 22 operational satellites
  - At least 5 sats above 5° elevation
  - PDOP mostly better than 3
- 2 additional sats in eccentric orbits
  - Not in almanac
  - Broadcast ephemerides (unhealthy)
- Exceptional SISRE:
  - ~20 cm RMS
  - ~40 cm 95%
  - Key to accurate point positioning





From https://www.glonass-iac.ru/

Galileo Point Positioning



- Geodetic receiver and antenna (BRUX)
- E1+E5a code and carrier phase
- Kinematic positioning using with broadcast ephemerides
- Forward filter, hourly re-initialization
- 17cm RMS horizontal, 30 cm RMS vertical, 34 cm 3D RMS

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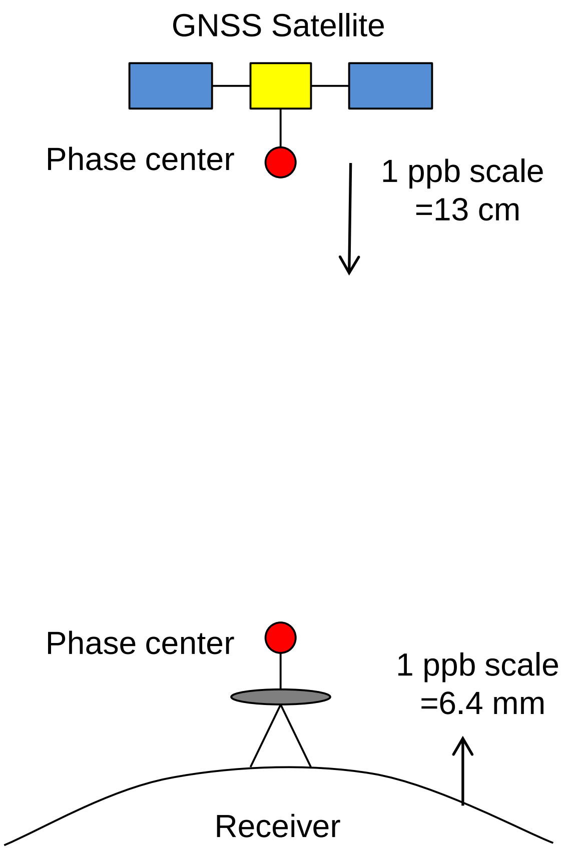
Galileo – New Services in E6

- E6B and E6C codes released Jan 2019
- High Accuracy Service:
  - Free of charge
  - Tender released early April 2019: “an open access service based on the provision of precise corrections (orbit, clock, biases, ionosphere) transmitted in the Galileo E6 signal (E6-B, data component), at a maximum rate of 448 bps per Galileo satellite connected to an uplink station allowing the user to achieve improved positioning performance”.
  - Gradual introduction (service area, accuracy)
- Commercial Authentication Service:
  - “a controlled access service based on the encrypted spreading codes in the E6 signal (E6-C, pilot tone). Service access will be achieved by the distribution of the relevant key material (NAVSEC keys)”.

Galileo – Defining the Scale of the Geodetic Reference Frame

- GNSS contributes to International Terrestrial Reference Frame (ITRF) through coordinates of GNSS stations
- Estimated station height depends on phase center offset and variations of satellite and receiver antennas
- GPS, GLONASS:
  - Scale inherited from SLR and VLBI
  - Calibrated receiver antenna patterns
  - Estimated satellite antenna patterns
- Galileo:
  - Calibrated satellite antenna patterns
  - Calibrated receiver antenna patterns
  - Estimation of GNSS scale becomes feasible



GPS Flex Power

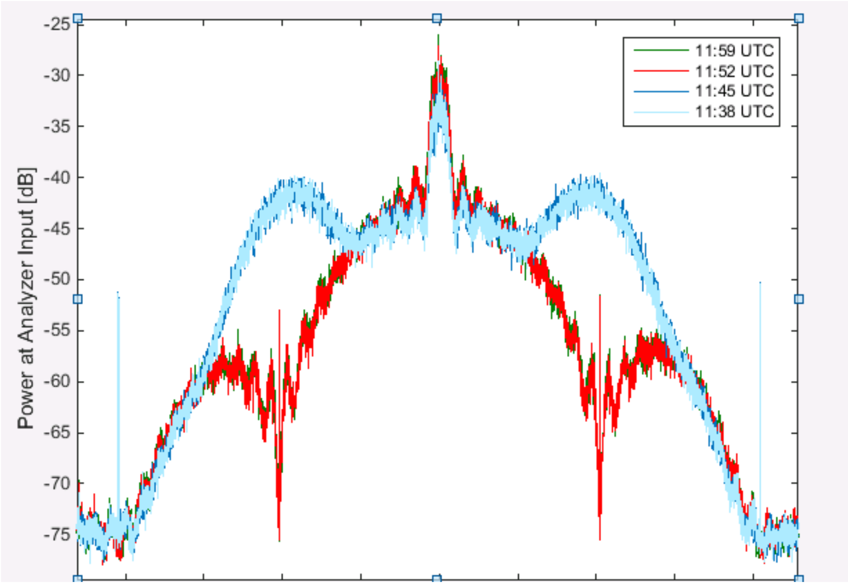
- Change of transmit power among signals for improved jamming resistance
- Exercised in various test campaigns and operations since 2017
- Available on IIR-M and IIF satellites

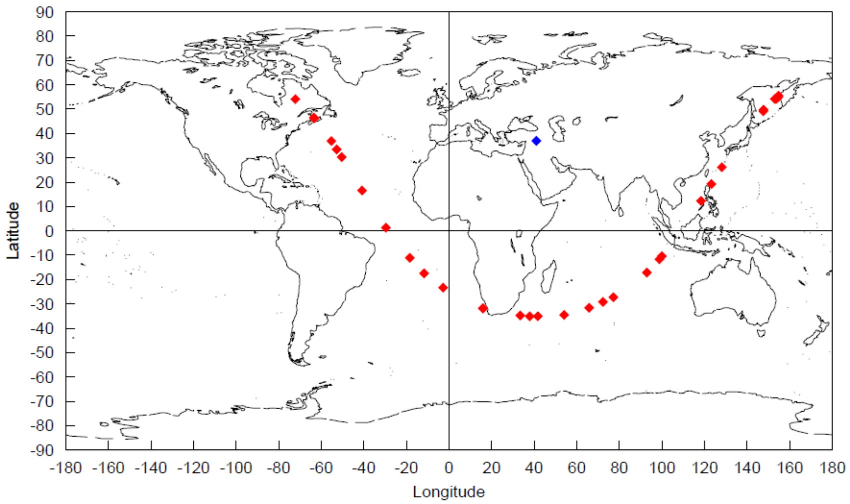
#	Sats	f	Duration	Region	Descritpion
1	IIF	L1	since 2017/27	centered at 41°E, 37°N	C/A and P(Y) power increased by 2.5 dB
2	IIR-M IIF	L1 L2	2018/103-107	Global	6 dB/5 dB P(Y) power increase on L1/L2
3	IIR-M IIF	L1 L2	2018/117, 121, 124 2:00 – 13:00 UTC	centered at 115°W, 40°N	Sum of L1+L2 P(Y) power increased by 9 to 11 dB; IIR-M: L1 C/A power reduced by 2-3 dB

GPS Flex Power

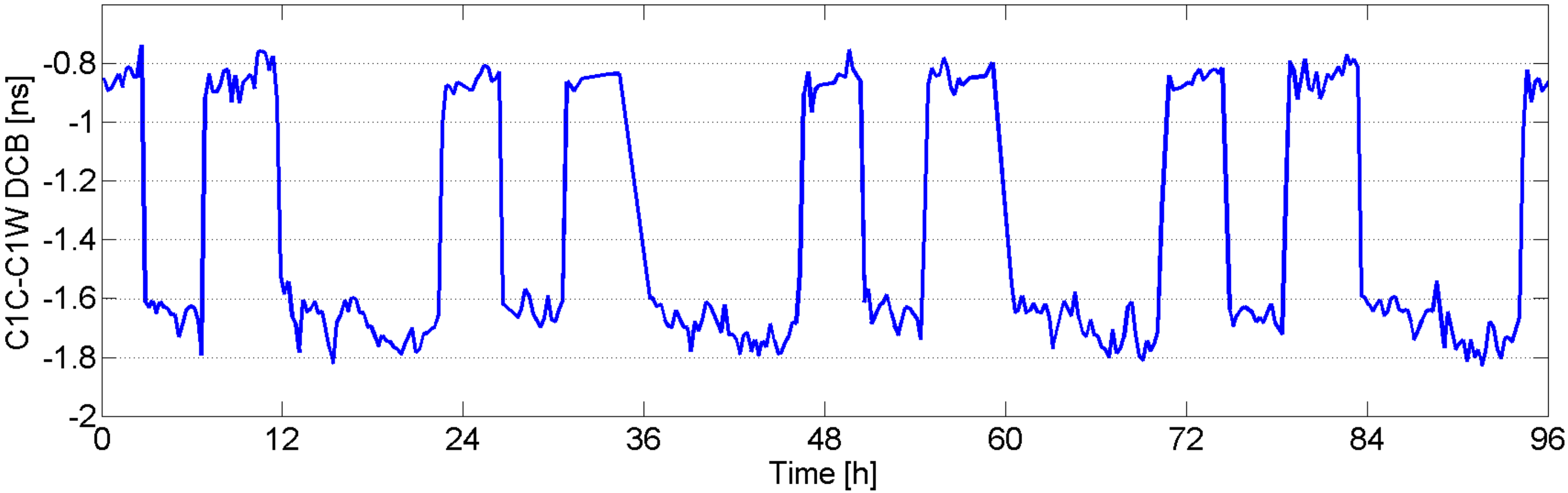
- M-code deactivated
- Power from M-code and intermodulation product distributed to C/A (or L2C) and P(Y) signals
- Total transmit power reduced (#1) or retained (#2) or unknown (#3)

- IIF flex power transitions triggered by visibility in area of interest





GPS Flex Power – User Impact



- Differential code bias variations at 1 ns level (subdaily; not covered by CNAV intersignal correction)
- C/N_0 changes for L1 C/A and semi-code less L1/L2 P(Y) tracking
- C/A-P(Y) phase relations unaffected (?)
- SPP users not affected; tolerable impact on precise point positing

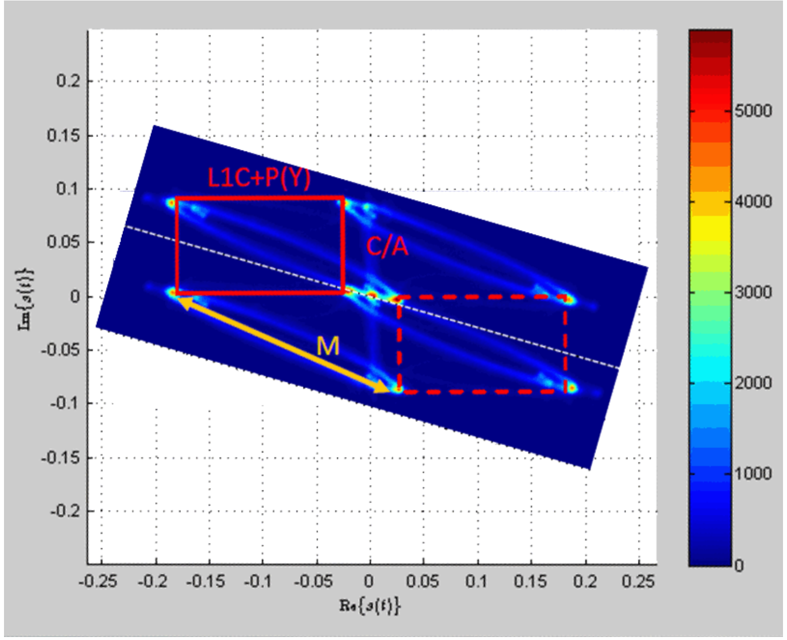
GPS III – A New Kid inTown

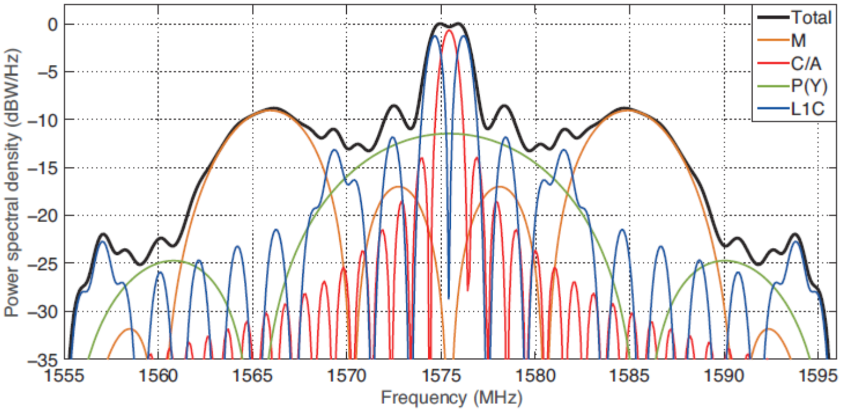
- GPS III-1 launched 23 Dec 2018
- Transmits as PRN 4 since 8 Jan. 2019
- Unhealthy, not in almanac
- Tracked and processed by International GNSS Service

- New platform (Lockheed Martin)
- First satellite transmitting L1C signal

GPS III – Signals

- New (mostly) digital signal generation
  - Very clean signals
  - Full coherency of L1, L2, L5 signals (unlike IIF)
- Five signals on L1
  - C/A-code
  - L1C data, L1C pilot, P(Y)-code
  - M-code
- Use of separate M-code transmit chain
- "Weighted voting" multiplexing scheme for L1C-(d,p) and P(Y)
  - Majority voting combination Interlacing of raw L1C-p, P(Y)





(GPS World March 2019)

GPS III Metadata

- Precise GNSS data processing relies on various spacecraft
- GPS III Phase center offsets (PCO) released right after launch ☺
  - Individual PCOs for L1, L2, L5
  - Surprisingly good agreement (6 cm) with first L1/L2 PCO estimates of F. Dilssner (ESA)
  - Important for GPS contribution to reference frame scale!
- Estimated phase variations +/- 15 mm
- Only coarse mass and size available for non-gravitational force modeling
- Attitude control law for rapid noon/midnight turns so far unknown

Public Availability of Metadata

	GPS	GLO	GAL	BDS-2	BDS-3S	BDS-3	QZSS	IRNSS
Mass	(L)	L	P	(L)	(L)	(L)	P	(L)
CoM			P	L			P	L
PCO/PCV	E,(P)/E	E	P	E,L/E	E,L/--	E,L/--	P	L/--
LRA offset	n/a	L	P	L	L	(L)	P	P?
Coarse geometry	(L)	(L)	P	L	(L)	(L)	P	L
Detailed geometry							(P)	
Optical properties	(L)		P	(E)			(P)	
Transmit Power	(M)	M	M	(M)			P	
Nominal Attitude	(L)	L	P	L	L	L	P	L
Detailed Attitude	(E)	(E)	(E)	(E)	(E)	(E)	(E)	
Maneuvers				(L)			P	

P: Provider; L: Literature; E: Estimated; M: Measured; () incomplete

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Summary and Conclusions

- Worldwide GNSSs are continuously evolving
  - Galileo and global BeiDou-3 system approaching full deployment
- Plethora of signals in various frequency bands
  - Open and regulated signals in all systems
  - Great diversity of advanced modulation schemes
  - Digital signal generation units offer improved signal quality (low biases!)
- What matters?
  - Trend to high accuracy services (QZSS, Galileo, …)
  - Cyber security, jamming and spoofing protection (GPS OCX, planned Galileo O/S and C/S authentication)
- GNSS for science and technology
  - Needs close interaction of science community, system providers and equipment manufacturers
  - Availability of proper satellite metadata is vital for high accuracy GNSS