For JAXA R&D

PPP - Models, Algorithms and Implementations (3)

Tokyo Univ. of Marine Science and Technology (TUMSAT)

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2019-11-01 @Tokyo, Japan

PPP - Models, Algorithms and Implementation

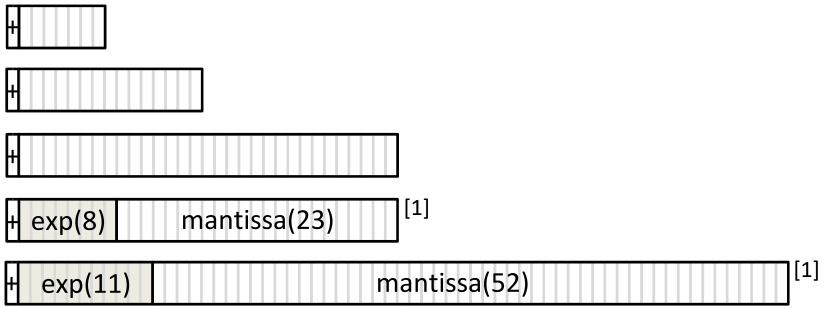
1. 2019-10-04 **PPP models**
   geometric range, ionosphere, troposphere, antenna PCV, earth tides, wind-up, relativity, biases, coordinates
2. 2019-10-18 **PPP algorithms**
   SPP, LSQ, GN, EKF, noise-model, RAIM/QC, LAPACK/BLAS
3. 2019-11-01 **PPP data handling**
   LC, interpolation, slip detection, RINEX, SP3, ANTEX, RTCM, CSSR
4. 2019-11-22 **PPP-AR**
   UPD/FCB, EWL/WL/NL, ILS, LAMBDA, TCAR, PAR, validation
5. 2019-12-06 **INS integration**
   INS sensors, Inertial navigation, INS integration
6. 2019-12-20 **POD of satellites**
   orbit element, orbit model, reduced-dynamic,
   ECI-ECEF transformation, precession/nutation, EOP

(1.5 h / session)

PPP Data Handling

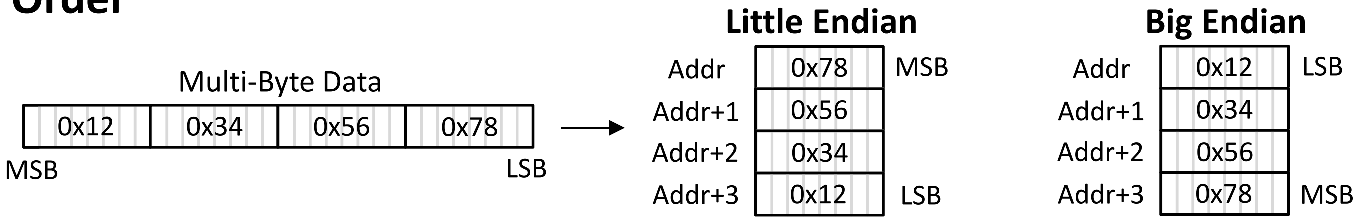
Data Representation

Numeric Representation (Binary)



	Size (bytes)	Range	Decimal Digits
int8_t	1	-128 ~ 127	2.11
int16_t	2	-32768 ~ 32767	4.52
int32_t	4	-2147483648 ~ 2147483647	9.33
float (SP)	4	-3.40 x 10^{38} ~ -3.40 x 10^{38}	7.22
double (DP)	8	-1.80 x 10^{308} ~ 1.80 x 10^{308}	15.95

Byte Order



Multi-Byte Data

0x12	0x34	0x56	0x78
MSB			LSB

Little Endian

Addr	0x78	MSB
Addr+1	0x56	
Addr+2	0x34	
Addr+3	0x12	LSB

x86 (Intel, AMD)

ARM

Big Endian

Addr	0x12	LSB
Addr+1	0x34	
Addr+2	0x56	
Addr+3	0x78	MSB

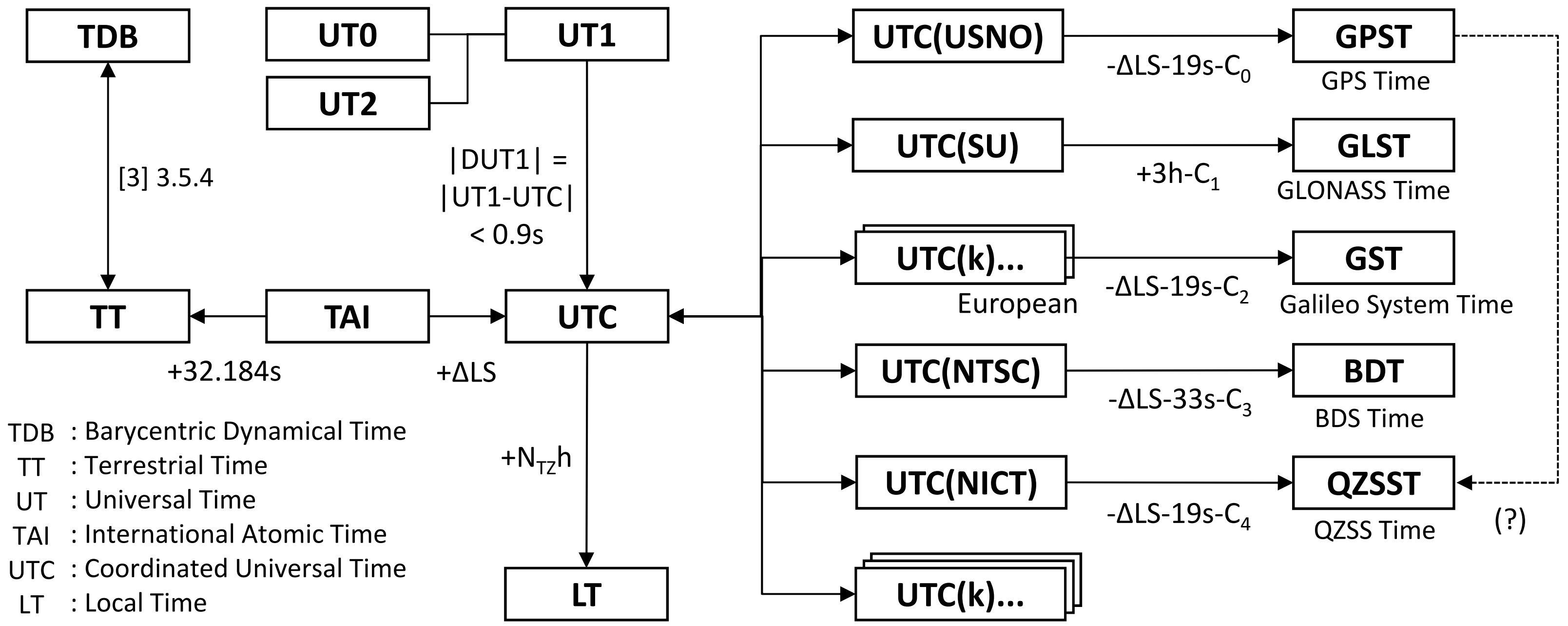
SPARC, JVM

Numerical Errors

	Example
Round-off errors	`(float)1.23456789e+0 -> 1.234568e+0`
Truncation errors	`-`
Loss of significance (subtractive cancellation)	`1.23456789e+0 - 1.23456786e+0 -> 2.0e-8`
Information loss	`1.23456789e+0 + 3.45678901e-9 -> 1.23456789e+0`
Overflow and underflow	`(int8_t)120 + (int8_t)10 -> -126`

[1] IEEE Std 754-2019, IEEE Standard for Floating Point Arithmetic

Time System



TDB

UT0

UT2

UT1

[3] 3.5.4

|DUT1| =
|UT1-UTC|
< 0.9s

TT

TAI

UTC

+32.184s

+ΔLS

$+N_{TZ}h$

LT

UTC(USNO) → GPST (GPS Time): $-\Delta LS-19s-C_0$

UTC(SU) → GLST (GLONASS Time): $+3h-C_1$

UTC(k)... European → GST (Galileo System Time): $-\Delta LS-19s-C_2$

UTC(NTSC) → BDT (BDS Time): $-\Delta LS-33s-C_3$

UTC(NICT) → QZSST (QZSS Time): $-\Delta LS-19s-C_4$

GPST → QZSST (?)

UTC(k)...

TDB : Barycentric Dynamical Time
TT : Terrestrial Time
UT : Universal Time
TAI : International Atomic Time
UTC : Coordinated Universal Time
LT : Local Time

UTC - TAI (ΔLS) [1]

Date/Time (UTC)	UTC-TAI	Date/Time (UTC)	UTC-TAI
1981-07-01 00:00:00 ~	-20 s	1994-07-01 00:00:00 ~	-29 s
1982-07-01 00:00:00 ~	-21 s	1996-01-01 00:00:00 ~	-30 s
1983-07-01 00:00:00 ~	-22 s	1997-07-01 00:00:00 ~	-31 s
1985-07-01 00:00:00 ~	-23 s	1999-01-01 00:00:00 ~	-32 s
1988-01-01 00:00:00 ~	-24 s	2006-01-01 00:00:00 ~	-33 s
1990-01-01 00:00:00 ~	-25 s	2009-01-01 00:00:00 ~	-34 s
1991-01-01 00:00:00 ~	-26 s	2012-07-01 00:00:00 ~	-35 s
1992-07-01 00:00:00 ~	-27 s	2015-07-01 00:00:00 ~	-36 s
1993-07-01 00:00:00 ~	-28 s	2017-01-01 00:00:00 ~	-37 s

UTC - UTC(k) (in 2019) [2]

Time Diff.	May 31	June 30	July 30	Aug 29	Sep 28
UTC-UTC(USNO)	2.7 ns	-0.3 ns	1.3 ns	2.8 ns	2.6 ns
UTC-UTC(SU)	0.9 ns	0.5 ns	0.1 ns	-0.2 ns	0.1 ns
UTC-UTC(CH)	-4.5 ns	-1.3 ns	0.1 ns	2.6 ns	0.4 ns
UTC-UTC(CNES)	12.1 ns	-14.8 ns	6.1 ns	26.3 ns	5.6 ns
UTC-UTC(DLR)	737.6 ns	-	861.0 ns	947.0 ns	1012.6 ns
UTC-UTC(NTSC)	1.5 ns	-0.2 ns	0.6 ns	3.2 ns	1.8 ns
UTC-UTC(NICT)	-0.4 ns	-1.3 ns	-1.4 ns	1.1 ns	4.4 ns
C_0 (GPST)	4.9 ns	1.4 ns	4.1 ns	4.9 ns	4.6 ns
C_1 (GLST)	24.9 ns	25.0 ns	29.3 ns	28.1 ns	29.2 ns

[1] International Earth Rotation and Reference System Service (IERS) Bulletin C (https://www.iers.org/)

[2] Bureau International Poids et Mesures (BIPM) Circular T (https://www.bipm.org/)

[3] D. A. Vallado, Fundamentals of Astrodynamics and Application, 2nd edition, Space Technology Library, 2001

Time Representation

Requirements

Very wide dynamic range: 0.001 ns (= 0.3 mm) ~ 200 years (6.3 x 10^{21} = 72.4 bits)

Continuous time scale to avoid bothersome clock jump handling

Easy to convert time to/from conventional representations (calendar date/time, UTC, LT)

Unix Time (POSIX Time)

Number of seconds elapsed since Unix epoch (0:00:00 UTC, Jan 1, 1970)

Overflow after 2038-01-19 03:14:07 UTC in **time_t** as a signed 32 bits int

Time jumps back or forward after leap second insertion or deletion

Not uniform time scale due to "SLEW" mode by some NTP implementations in real-time

Julian Date/Modified Julian Date (JD/MJD)

JD: Continuous count of days since Julian epoch (12:00:00 UT, Jan 1, 4713 BC)

MJD = JD - 240000.5 (days)

Time scale usually defined by UT. Hard to handle leap second deletion or insertion

GPS Time (GPST)

Continuous time scale (no leap seconds) since GPST start (0:00:00 UTC, Jan 6, 1980)

Represented as GPS WN (week number starting at 0) and TOW (time of week) in seconds

Rollover problems by using 8 bits (almanac) or 10 bits (ephemeris) WN

Time in RTKLIB

```
typedef struct {  // RTKLIB time struct (12 or 16 Bytes)
    time_t time;  // time (s) expressed by standard time_t (4 or 8 Bytes) in GPS Time
    double sec;   // fraction of second under 1 s
} gtime_t;
```

Data Formats

RINEX (Receiver Independent Exchange Format)

Developed and maintained by IGS since 1990s for PP and data archive

For observation data (OBS), navigation data (NAV), meteorological data (MET) and extensions

RTCM (Radio Technical Commission for Maritime Services)

Developed and maintained by RTCM SC-104 (special-committee 104) for DGNSS, RTK and PPP

RTCM 2 (version 2) and RTCM 3 (version 3). RTCM 3 is not compatible to RTCM 2.

Compact and portable binary format

BINEX (Binary Exchange Format)

Developed and maintained by UNAVCO (university NAVSTAR consortium) for RT or PP and archive

Compact and portable binary format

Proprietary Formats by GNSS Receiver Vendors

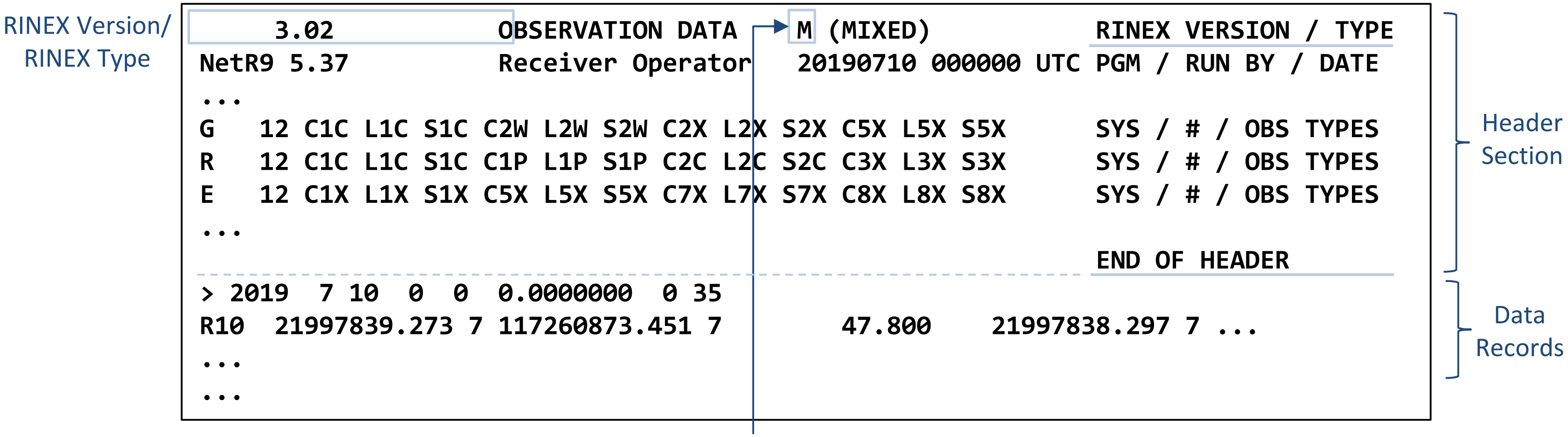
RT17/RT27, CMR/CMR+ (Trimble), GREIS (JAVAD), NovAtel, SBF (Septentrio), UBX (u-blox), ...

Example of Data Sizes[*1]

Format	**Data Size (Bytes)**					
	RTCM 3 *1	**BINEX** *1	**CMR+** *1	**RINEX 2.12** *2	**RINEX 3.02** *2	**Compressed RINEX** *3
OBS Data	2,387,289	5,140,927	1,137,059	83,386,990	29,225,908	6,709,900
NAV Data	-			33,022	32,794	-

*1 GNSS receiver: Trimble BD982, Data sampling: 1 Hz x 1 H, System: GPS/GLO/GAL/BDS/QZS/SBS, *2 Converted from BINEX by RTKCONV 2.4.3 b32, *3 Converted from RINEX 3.02 by RNX2CNX 4.08

RINEX



```
      3.02           OBSERVATION DATA    M (MIXED)           RINEX VERSION / TYPE
NetR9 5.37           Receiver Operator   20190710 000000 UTC PGM / RUN BY / DATE
...
G   12 C1C L1C S1C C2W L2W S2W C2X L2X S2X C5X L5X S5X      SYS / # / OBS TYPES
R   12 C1C L1C S1C C1P L1P S1P C2C L2C S2C C3X L3X S3X      SYS / # / OBS TYPES
E   12 C1X L1X S1X C5X L5X S5X C7X L7X S7X C8X L8X S8X      SYS / # / OBS TYPES
...
                                                            END OF HEADER
> 2019  7 10  0  0  0.0000000  0 35
R10  21997839.273 7 117260873.451 7       47.800    21997838.297 7 ...
...
...
```

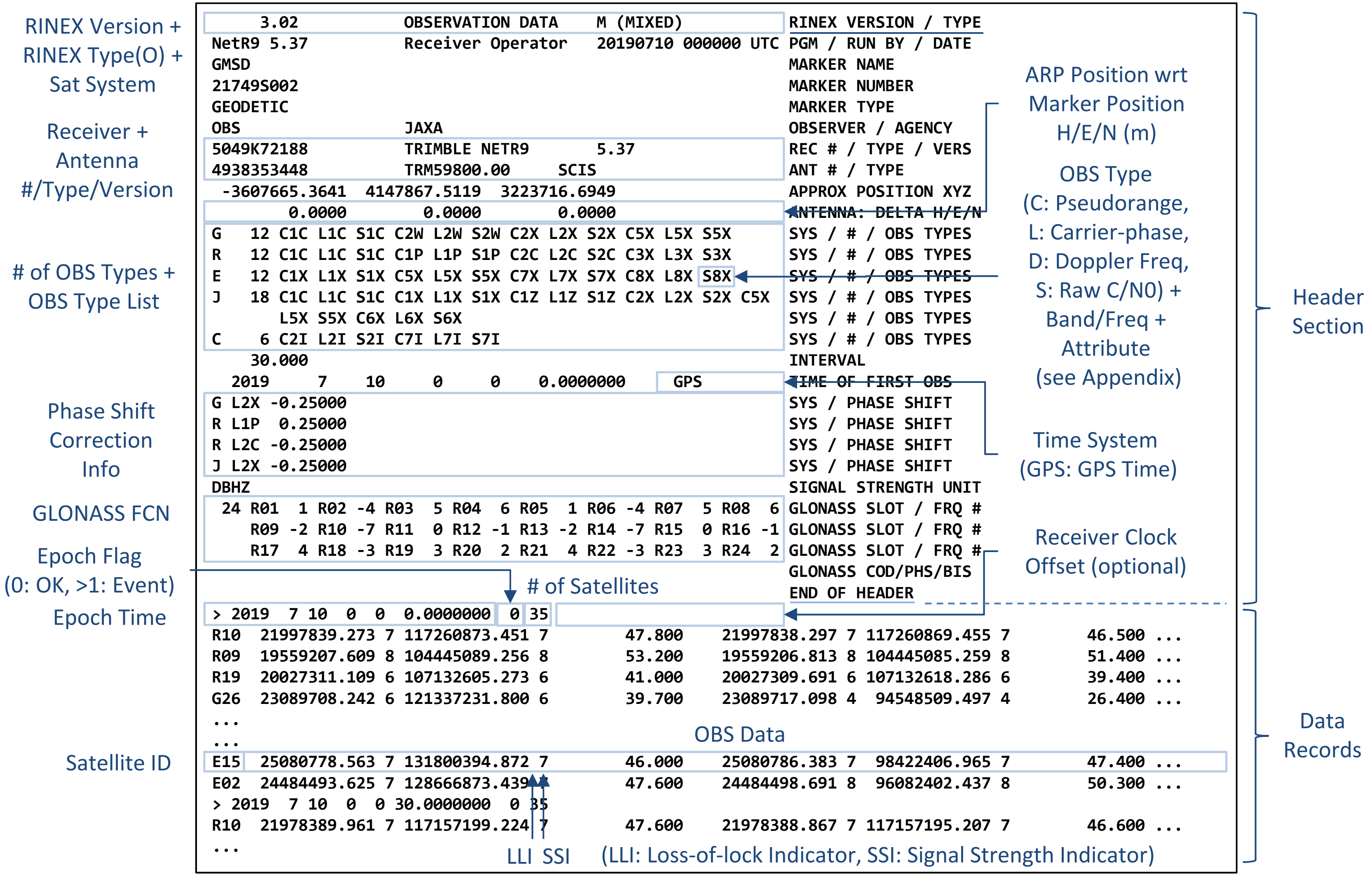
Sat System (G: GPS, R: GLONASS, E: Galileo, J: QZSS, C: BeiDou, I: IRNSS, S: SBAS, M: Mixed)

RINEX Version	RINEX Type																
	Observation Data [1]							Navigation Data [1]							MET [1]	CLK [2]	SBAS[3]
	G	R	E	J	C	I	S	G	R	E	J	C	I	S			
2.10	O	O	-	-	-	-	O	N	G	-	-	-	-	H	M	-	B
2.11	O	O	O	-	-	-	O	N	G	-	-	-	-	H	M	-	-
2.12	O	O	O	-	O	-	O	N	G	N	-	-	-	H	M	-	-
3.00	O	O	O	-	-	-	O	N	N	N	-	-	-	N	M	C	-
3.01	O	O	O	-	O	-	O	N	N	N	-	-	-	N	M	C	-
3.02	O	O	O	O	O	-	O	N	N	N	N	N	-	N	M	C	-
3.03	O	O	O	O	O	O	O	N	N	N	N	N	N	N	M	-	-
3.04	O	O	O	O	O	O	O	N	N	N	N	N	N	N	M	-	-

MET: Meteorological data, CLK: RINEX clock extension, SBAS: GEO SBAS broadcast data extension

[1] RINEX - The receiver independent exchange format version 3.04, Nov 2018, [2] RINEX extension to handle clock information, version 3.02, Sep 2010, [3] Proposal for a new RINEX-type exchange file for GEO SBAS broadcast data, Sep 2004

RINEX 3 OBS



```
     3.02           OBSERVATION DATA    M (MIXED)           RINEX VERSION / TYPE
NetR9 5.37          Receiver Operator   20190710 000000 UTC PGM / RUN BY / DATE
GMSD                                                        MARKER NAME
21749S002                                                   MARKER NUMBER
GEODETIC                                                    MARKER TYPE
OBS                 JAXA                                    OBSERVER / AGENCY
5049K72188          TRIMBLE NETR9       5.37                REC # / TYPE / VERS
4938353448          TRM59800.00     SCIS                    ANT # / TYPE
 -3607665.3641  4147867.5119  3223716.6949                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G   12 C1C L1C S1C C2W L2W S2W C2X L2X S2X C5X L5X S5X      SYS / # / OBS TYPES
R   12 C1C L1C S1C C1P L1P S1P C2C L2C S2C C3X L3X S3X      SYS / # / OBS TYPES
E   12 C1X L1X S1X C5X L5X S5X C7X L7X S7X C8X L8X S8X      SYS / # / OBS TYPES
J   18 C1C L1C S1C C1X L1X S1X C1Z L1Z S1Z C2X L2X S2X C5X  SYS / # / OBS TYPES
       L5X S5X C6X L6X S6X                                  SYS / # / OBS TYPES
C    6 C2I L2I S2I C7I L7I S7I                              SYS / # / OBS TYPES
    30.000                                                  INTERVAL
  2019     7    10     0     0    0.0000000     GPS         TIME OF FIRST OBS
G L2X -0.25000                                              SYS / PHASE SHIFT
R L1P  0.25000                                              SYS / PHASE SHIFT
R L2C -0.25000                                              SYS / PHASE SHIFT
J L2X -0.25000                                              SYS / PHASE SHIFT
DBHZ                                                        SIGNAL STRENGTH UNIT
 24 R01  1 R02 -4 R03  5 R04  6 R05  1 R06 -4 R07  5 R08  6 GLONASS SLOT / FRQ #
    R09 -2 R10 -7 R11  0 R12 -1 R13 -2 R14 -7 R15  0 R16 -1 GLONASS SLOT / FRQ #
    R17  4 R18 -3 R19  3 R20  2 R21  4 R22 -3 R23  3 R24  2 GLONASS SLOT / FRQ #
                                                            GLONASS COD/PHS/BIS
                                                            END OF HEADER
> 2019  7 10  0  0  0.0000000  0 35
R10  21997839.273 7 117260873.451 7        47.800    21997838.297 7 117260869.455 7        46.500 ...
R09  19559207.609 8 104445089.256 8        53.200    19559206.813 8 104445085.259 8        51.400 ...
R19  20027311.109 6 107132605.273 6        41.000    20027309.691 6 107132618.286 6        39.400 ...
G26  23089708.242 6 121337231.800 6        39.700    23089717.098 4  94548509.497 4        26.400 ...
...
...
E15  25080778.563 7 131800394.872 7        46.000    25080786.383 7  98422406.965 7        47.400 ...
E02  24484493.625 7 128666873.439 7        47.600    24484498.691 8  96082402.437 8        50.300 ...
> 2019  7 10  0  0 30.0000000  0 35
R10  21978389.961 7 117157199.224 7        47.600    21978388.867 7 117157195.207 7        46.600 ...
...
```

RINEX Version + RINEX Type(O) + Sat System

Receiver + Antenna #/Type/Version

# of OBS Types + OBS Type List

Phase Shift Correction Info

GLONASS FCN

Epoch Flag (0: OK, >1: Event)

Epoch Time

Satellite ID

ARP Position wrt Marker Position H/E/N (m)

OBS Type (C: Pseudorange, L: Carrier-phase, D: Doppler Freq, S: Raw C/N0) + Band/Freq + Attribute (see Appendix)

Time System (GPS: GPS Time)

Receiver Clock Offset (optional)

# of Satellites

OBS Data

LLI SSI (LLI: Loss-of-lock Indicator, SSI: Signal Strength Indicator)

Header Section

Data Records

[1] IGS RINEX WG and RTCM-SC104, RINEX - The receiver independent exchange format version 3.04, Nov 2018

RINEX 3 NAV

RINEX Version + RINEX Type(N) + Sat System

```
     3.03           N: GNSS NAV DATA    M: MIXED            RINEX VERSION / TYPE
MergeMNfile.tcl     IGS                 20190719 075936 GMT PGM / RUN BY / DATE
GPSA   4.6566D-09  1.4901D-08 -5.9605D-08 -1.1921D-07       IONOSPHERIC CORR
GPSB   8.1920D+04  8.1920D+04 -6.5536D+04 -5.2429D+05       IONOSPHERIC CORR
...
GPUT  2.7939677238D-09 1.154631946D-14 405504 2061          TIME SYSTEM CORR
GLUT -4.6566128731D-10 0.000000000D+00      0    0          TIME SYSTEM CORR
GAUT  9.3132257462D-09-5.329070518D-15 172800 2061          TIME SYSTEM CORR
...
    18    18  1929     7                                    LEAP SECONDS
                                                            END OF HEADER
```

Ionospheric Correction Parameters (optional)

GNSS Time Difference Parameters (optional)

Leap seconds (optional)

Header Section

Satellite ID

GPS/GAL/BDS/QZS Ephemeris and SV Clock Parameters

```
G01 2019 07 10 00 00 00-6.297975778580E-05-1.034550223270E-11 0.000000000000E+00
     7.400000000000E+01 6.406250000000E+00 4.275535236060E-09-1.468053231860E+00
     3.315508365630E-07 9.019587654620E-03 7.307156920430E-06 5.153651456830E+03
     2.592000000000E+05 1.434236764910E-07 2.552552807090E+00-4.284083843230E-08
     9.763611140680E-01 2.432812500000E+02 7.320008488990E-01-7.944973797190E-09
     4.535903224290E-10 1.000000000000E+00 2.061000000000E+03 0.000000000000E+00
     2.000000000000E+00 0.000000000000E+00 5.587935447690E-09 7.400000000000E+01
     2.520180000000E+05 4.000000000000E+00
```

0	Time_of_Clock(TOC)	SV_clock_bias(s)	SV_Clk_Drift(s/s)	SV_Clk_rate(s/s2)
1	IODE*1	Crs(m)	Delta_n(rad/s)	M0(rad)
2	Cuc(rad)	e(eccentricity)	Cus(rad)	sqrt(A)(sqrt(m))
3	Time_of_ephem(TOE)	Cic(rad)	OMEGA0(rad)	Cis(rad)
4	i0(rad)	Crc(rad)	omega(rad)	OMEGA_DOT(rad/s)
5	IDOT(rad/s)	Code_on_L2_ch*2	GPS_week_#*3	L2_P_data_flag*4
6	SV_accuracy(m)*5	SV_health*6	TGD(s)*7	IODC*8
7	Transmit_Time	Fit_interval(h)*9	Spare	Spare

...

*1 GAL: IOD_nav
   BDS: AODE
*2 GAL: Data_source
   BDS: Spare
*3 GAL: GAL_week_#
   BDS: BDT_week_#
*4 GAL,BDS: Spare
*5 GAL: SISA(m)
*6 BDS: SatH1
*7 GAL: BGD_E5a/E1(s)
   BDS: TGD1_B1/B3(s)
*8 GAL: BGD_E5b/E1(s)
   BGS: TGD2_B2/B3(s)
*9 GAL: Spare
   QZS: Fit_interval_flag
   BDS: AODC

Satellite ID

GLO Ephemeris and SV Clock Parameters

```
R01 2019 07 10 00 15 00 4.648976027966E-05 0.000000000000E+00 2.601000000000E+05
     1.750996093750E+04 1.717527389526E+00-9.313225746155E-10 0.000000000000E+00
     6.118407226562E+03 1.674188613892E+00 9.313225746155E-10 1.000000000000E+00
     1.752643945312E+04-2.299521446228E+00-1.862645149231E-09 0.000000000000E+00
```

0	Time_of_Clock(TOC)	SV_clock_bias(s)	SV_rel_freq_bias	Msg_frame_time(s)
1	Sat_position_X(km)	Vel_X_dot(km/s)	X_accel(km/s2)	health
2	Sat_position_Y(km)	Vel_Y_dot(km/s)	Y_accel(km/s2)	frequency_number
3	Sat_position_Z(km)	Vel_Z_dot(km/s)	Z_accel(km/s2)	Age_of_oper(days)

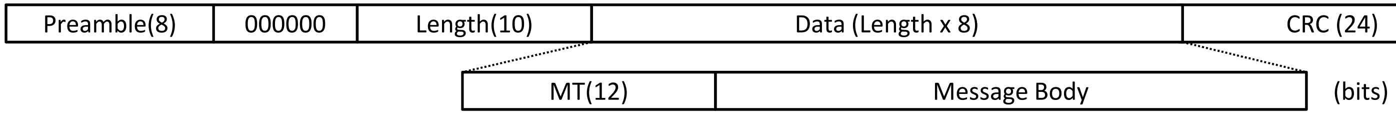
...

Data Records

[1] IGS RINEX WG and RTCM-SC104, RINEX - The receiver independent exchange format version 3.04, Nov 2018

RTCM 3

RTCM 3 Message [1]



Message		MT (Message Type)					
		GPS	GLONASS	Galileo	QZSS	BeiDou	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	-
MSM	MSM 1 (Compact P) *3	1071	1081	1091	1111	1121	1101
	MSM 2 (Compact PR) *3	1072	1082	1092	1112	1122	1102
	MSM 3 (Compact P+PR) *3	1073	1083	1093	1113	1123	1103
	MSM 4 (Full P+PR+CN) *3	1074	1084	1094	1114	1124	1104
	MSM 5 (Full P+PR+PRR+CN) *3	1075	1085	1095	1115	1125	1105
	MSM 6 (Full P+PR+CN+H) *3	1076	1086	1096	1116	1126	1106
	MSM 7 (Full P+PR+PRR+CN+H) *3	1077	1087	1097	1117	1127	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 10403.3, Differential GNSS (global navigation satellite system) services - version 3, Oct 2016

LC (Linear Combination)

LC of L1, L2, L5 Carrier Phase and Pseudorange

$$LC = a\Phi_{L1} + b\Phi_{L2} + c\Phi_{L5} + dP_{L1} + eP_{L2} + fP_{L5}$$

	LC	Coefficients						Wave Length (cm)	Ionos Effect wrt L1	Typical Noise (cm)
		a	b	c	d	e	f			
L1	L1 Carrier-Phase	1	-	-	-	-	-	19.0	1.0	0.3
L2	L2 Carrier-Phase	-	1	-	-	-	-	24.4	1.6	0.3
L5	L5 Carrier-Phase	-	-	1	-	-	-	25.5	1.8	0.3
LC/L3	L1-L2 Iono-Free Phase	C_1	C_2	-	-	-	-	-	0.0	0.9
$LC_{L1\text{-}L5}$	L1-L5 Iono-Free Phase	C_3	-	C_4	-	-	-	-	0.0	0.8
LG/L4	L1-L2 Geometry-Free Phase	1	-1	-	-	-	-	-	-0.6	0.4
$LG_{L2\text{-}L5}$	L2-L5 Geometry-Free Phase	-	1	-1	-	-	-	-	-0.1	0.4
EWL	Extra-Wide-Lane Phase	-	$\lambda_{EWL}/\lambda_{L2}$	$-\lambda_{EWL}/\lambda_{L5}$	-	-	-	586.1	-0.2	0.4
WL	Wide-Lane Phase	$\lambda_{WL}/\lambda_{L1}$	$-\lambda_{WL}/\lambda_{L2}$	-	-	-	-	86.2	-1.3	1.7
NL	Narrow-Lane Phase	$\lambda_{NL}/\lambda_{L1}$	$\lambda_{NL}/\lambda_{L2}$	-	-	-	-	10.7	1.3	1.7
MW	Melbourne-Wübbena WL	$\lambda_{WL}/\lambda_{L1}$	$-\lambda_{WL}/\lambda_{L2}$	-	$-\lambda_{NL}/\lambda_{L1}$	$-\lambda_{NL}/\lambda_{L2}$	-	86.2	0.0	21
MW_{EWL}	Melbourne-Wübbena EWL	-	$\lambda_{EWL}/\lambda_{L2}$	$-\lambda_{EWL}/\lambda_{L5}$	-	$-\lambda_{ENL}/\lambda_{L2}$	$-\lambda_{ENL}/\lambda_{L5}$	586.1	0.0	21
MP1	L1-Multipath	$2C_2-1$	$-2C_2$	-	1	-	-	-	0.0	30
MP2	L2-Multipath	$-2C_1$	$2C_1-1$	-	-	1	-	-	0.0	30
MP5	L5-Multipath	$-2C_3$	-	$2C_3-1$	-	-	1	-	0.0	30

$C_1 = \lambda_{L1}{}^2\lambda_{L2}{}^2/(\lambda_{L2}{}^2 - \lambda_{L1}{}^2) = 2.55, C_2 = -\lambda_{L2}{}^2\lambda_{L1}{}^2/(\lambda_{L2}{}^2 - \lambda_{L1}{}^2) = -1.55$, $C_3 = \lambda_{L1}{}^2\lambda_{L5}{}^2/(\lambda_{L5}{}^2 - \lambda_{L1}{}^2) = 2.26$, $C_4 = -\lambda_{L5}{}^2\lambda_{L1}{}^2/(\lambda_{L5}{}^2 - \lambda_{L1}{}^2) = -1.26$,

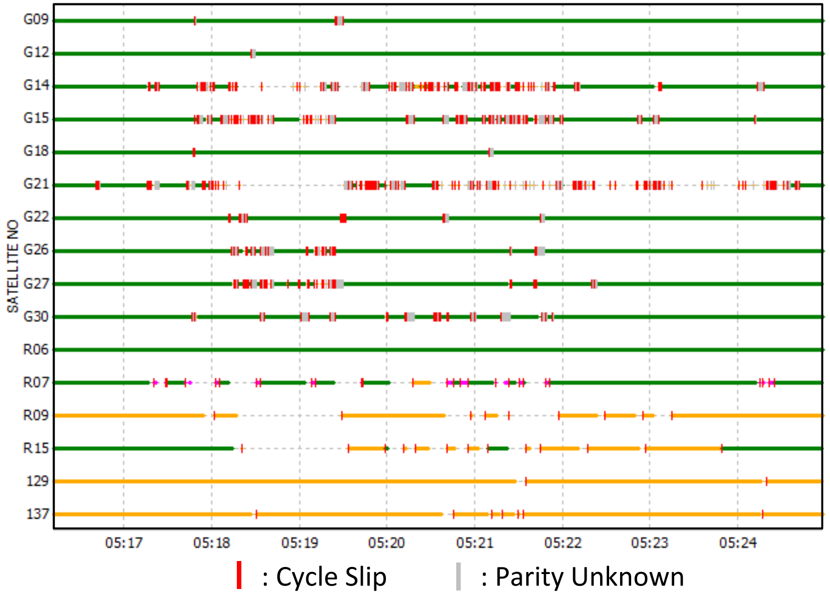
$\lambda_{WL} = \lambda_{L1}\lambda_{L2}/(\lambda_{L2} - \lambda_{L1}) = 86.2\,\text{cm}, \lambda_{NL} = \lambda_{L1}\lambda_{L2}/(\lambda_{L1} + \lambda_{L2}) = 10.7\,\text{cm}, \lambda_{EWL} = \lambda_{L2}\lambda_{L5}/(\lambda_{L5} - \lambda_{L2}) = 586.1\,\text{cm}, \lambda_{ENL} = \lambda_{L2}\lambda_{L5}/(\lambda_{L2} + \lambda_{L5}) = 12.5\,\text{cm}$

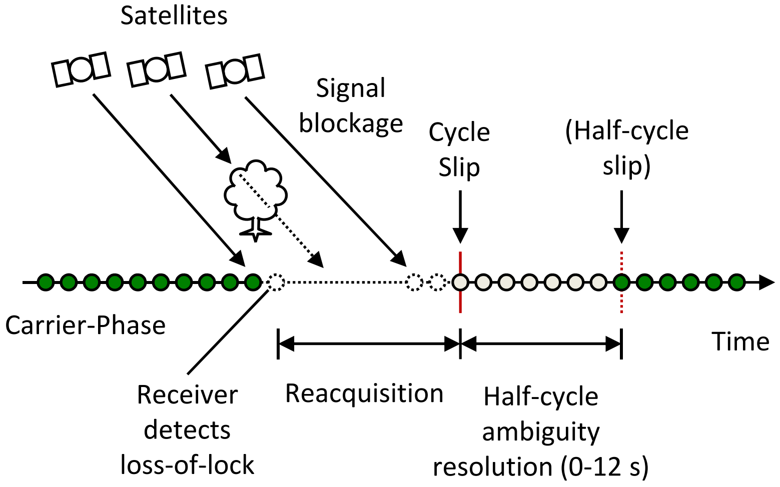
Cycle Slip

Definition

A sudden jump in carrier-phase measurements when the phase tracking loop (PLL) in receivers detects a temporary loss of lock due to signal blockage or some other disturbing factor. The carrier-cycle counter in the receiver restarts, causing a jump in the accumulated phase by an integer number of cycles.

Example of Cycle Slips





Cycle Slip Detection

Lock Time or LLI (loss-of-lock indicator)

Reversed lock time, lock time < time interval, potential loss-of-lock flag by LLI

Detect Jumps in LCs

LG LC (with polynomial fitting): $\Delta LG = \left| LG(t_i) - LG(t_{i-1}) \right| > THRES_{LG}$

MW LC with moving average: $\Delta MW = \left| \overline{MW(t_i \ldots t_{i+n-1})} - \overline{MW(t_{i-n} \ldots t_{i-1})} \right| > THRES_{MW}$

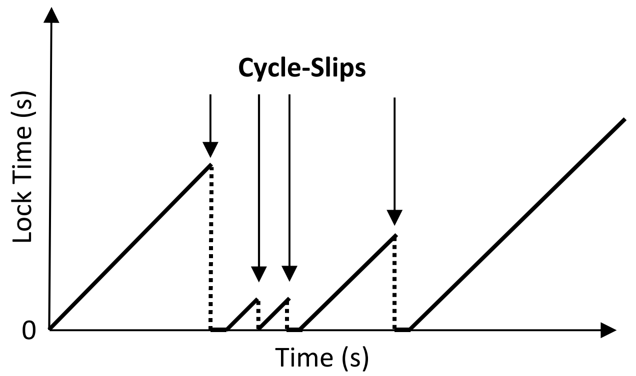
MPk LC with moving average: $\Delta MP_k = \left| \overline{MP_k(t_{i\ldots}\, t_{i+n-1})} - \overline{MP_k(t_{i-n} \ldots t_{i-1})} \right| > THRES_{MPk}$

Observed - Predicted Phase with Doppler

$\Delta\Phi_{Lk} = \left| \Phi_{Lk}(t_{i-1}) - \lambda_{Lk}(t_i - t_{i-1}) D_{Lk} - \Phi_{Lk}(t_i) \right| > THRES_{Lk}$ D_{Lk} : L_k Doppler Frequency (Hz)

Pre-fit or Post-fit Residuals Test in Navigation Filter

Lock Time Reversed by Cycle Slips



LG LC Jump by Cycle Slips (L1-L2) (cm)

		L1 Cycle Slip (cycle)								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
L2 Cycle Slip (cycle)	**0**	0.0	-24.4	-48.8	-73.3	-97.7	-122.1	-146.5	-170.9	-195.4
	1	19.0	**-5.4**	-29.8	-54.2	-78.7	-103.1	-127.5	-151.9	-176.3
	2	38.1	13.6	-10.8	-35.2	-59.6	-84.0	-108.5	-132.9	-157.3
	3	57.1	32.7	**8.2**	-16.2	-40.6	-65.0	-89.4	-113.9	-138.3
	4	76.1	51.7	27.3	**2.9**	-21.6	-46.0	-70.4	-94.8	-119.3
	5	95.1	70.7	46.3	21.9	**-2.5**	-27.0	-51.4	-75.8	-100.2
	6	114.2	89.8	65.3	40.9	16.5	**-7.9**	-32.3	-56.8	-81.2
	7	133.2	108.8	84.4	59.9	35.5	11.1	-13.3	-37.7	-62.2
	8	152.2	127.8	103.4	79.0	54.6	30.1	**5.7**	-18.7	-43.1

Receiver Biases and Phase Shift

DCB (Differential Code Bias)

Biases in pseudorange between different codes tracked (e.g. GPS L1C/A - L1P(Y))

Satellite DCB should be corrected by external DCB info (T_{GB}, P1-C1 DCB, P2-C2 DCB ...)

Receiver DCB usually implicitly estimated as in the receiver clock biases as LC

ISB (Inter System Bias)

Biases in pseudorange and phase between different systems (e.g. GPS L1C/A - GAL E1B)

Hard to incorporated ISB in estimation due to unstable behavior (varied by receiver F/W updates)

IFB (Inter Frequency Bias)

Biases in pseudorange and phase between different FCN GLONASS satellites (e.g. R01 - R02)

IFB in pseudorange should be estimated explicitly or corrected by external calibration data

IFB in phase is hard to be corrected due to instability including antennas and cables

ISTB (Inter Satellite Type Bias) [1]

Biases in pseudorange and phase between different BDS satellite types (e.g. BDS GEO - IGSO)

Quarter Cycle Phase Shift

Quarter cycle phase shift in phase between different codes tracked (e.g. GPS L2P(Y) - L2C)

All phases on the same frequency should be aligned by the latest RINEX or RTCM 3, but needs careful handling of OBS data in vendor proprietary formats

[1] N. Nadarajah et al., The mixed-receiver BeiDou inter-satellite-type-bias and its impact on RTK positioning, GPS Solution, 2014

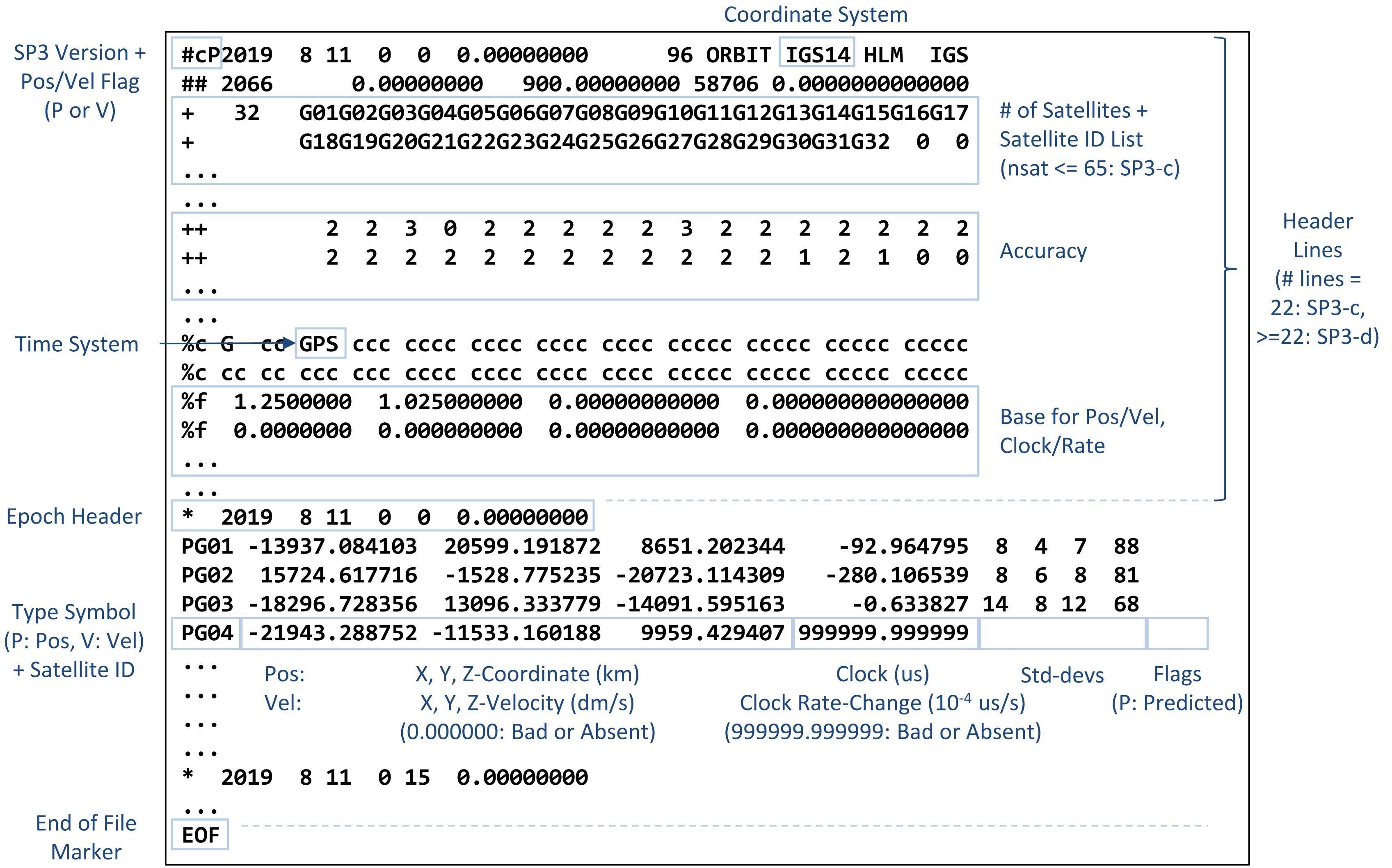
Precise Ephemeris

IGS Products (Satellite Orbit, Clock and EOP) [1]

Product			Final (IGS)	Rapid (IGR)	Ultra-Rapid (IGU)		Broadcast
					Observed	Predicted	
Accuracy	**Orbit**	**GPS**	~ 2.5 cm	~ 2.5 cm	~ 3 cm	~ 5 cm	~ 100 cm
		GLONASS	~ 3 cm	-	-	-	-
	Clock (GPS)	**RMS**	~ 75 ps	~ 75 ps	~ 150 ps	~ 3 ns	~ 5 ns
		STD	~ 20 ps	~ 25 ps	~ 50 ps	~ 1.5 ns	~ 2.5 ns
	EOP	**PM**	~ 30 uas	~ 50 uas	~ 50 uas	~ 300 uas	-
		PM Rate	~ 150 uas/day	~ 250 uas/day	~ 250 uas/day	~ 300 uas/day	-
		LOD	~ 10 us	~ 10 us	~ 10 us	~ 50 us	-
Sample Interval	**Orbit**		15 min	15 min	15 min		-
	Clock	**Satellite**	30 s	5 min	15 min		-
		Station	5 min	-	-		-
	EOP		1 day	1 day	1 day		-
Update Interval			1 week (Thursday)	1 day (17:00 UTC)	6 h (3:00, 9:00, 15:00, 21:00 UTC)		-
Latency			12 ~ 18 days	17 ~ 41 h	3 ~ 9 h	Realtime	Realtime
Format			SP3-c, RINEX Clock, IGS ERP ver.2	SP3-c, RINEX Clock, IGS ERP ver.2	SP3-c, IGS ERP ver.2		RINEX 2 (NAV)
Combination of IGS ACs			COD, EMR, ESA, GFZ, GRG, JPL, MIT, NGS, SIO	COD, EMR, ESA, GFZ, JPL, NGS, SIO, USN, WHU	COD, EMR, ESA, GFZ, NGS, SIO, USN		-

[1] http://www.igs.org/products

SP3



Coordinate System

SP3 Version + Pos/Vel Flag (P or V)

```
#cP2019  8 11  0  0  0.00000000      96 ORBIT IGS14 HLM  IGS
## 2066      0.00000000   900.00000000 58706 0.0000000000000
+   32   G01G02G03G04G05G06G07G08G09G10G11G12G13G14G15G16G17
+        G18G19G20G21G22G23G24G25G26G27G28G29G30G31G32  0  0
...
...
++         2  2  3  0  2  2  2  2  2  3  2  2  2  2  2  2  2
++         2  2  2  2  2  2  2  2  2  2  2  2  1  2  1  0  0
...
...
%c G  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
...
...
*  2019  8 11  0  0  0.00000000
PG01 -13937.084103  20599.191872   8651.202344    -92.964795  8  4  7  88
PG02  15724.617716  -1528.775235 -20723.114309   -280.106539  8  6  8  81
PG03 -18296.728356  13096.333779 -14091.595163     -0.633827 14  8 12  68
PG04 -21943.288752 -11533.160188   9959.429407 999999.999999
...
...
...
...
*  2019  8 11  0 15  0.00000000
...
EOF
```

# of Satellites + Satellite ID List (nsat <= 65: SP3-c)

Accuracy

Header Lines (# lines = 22: SP3-c, >=22: SP3-d)

Time System

Base for Pos/Vel, Clock/Rate

Epoch Header

Type Symbol (P: Pos, V: Vel) + Satellite ID

Pos: X, Y, Z-Coordinate (km) Clock (us) Std-devs Flags

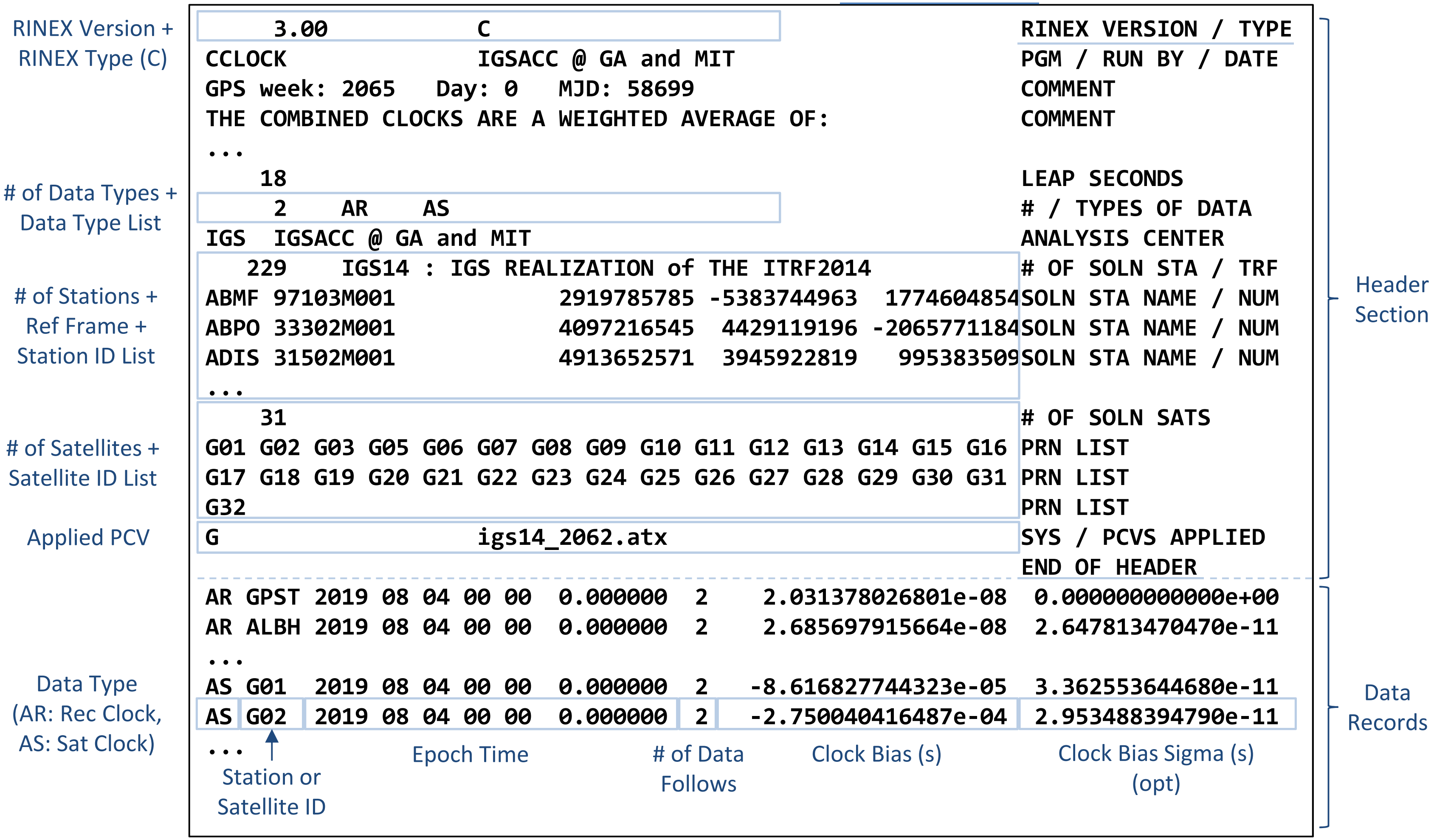
Vel: X, Y, Z-Velocity (dm/s) Clock Rate-Change (10^{-4} us/s) (P: Predicted)

(0.000000: Bad or Absent) (999999.999999: Bad or Absent)

End of File Marker

[1] S. Hilla, The extended standard product 3 orbit format (SP3-d), Feb 2016

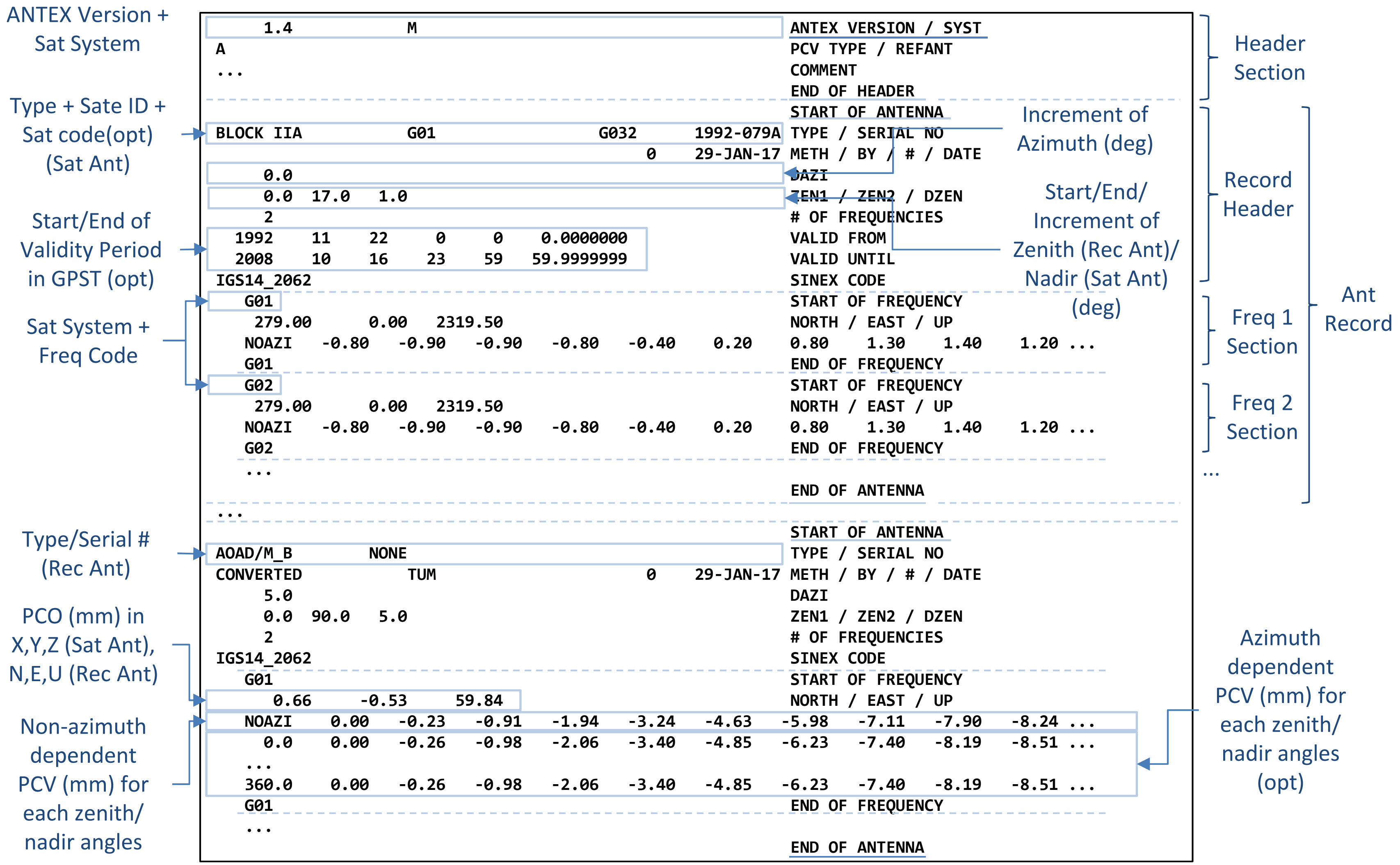
RINEX Clock



```
     3.00           C                                       RINEX VERSION / TYPE
CCLOCK              IGSACC @ GA and MIT                     PGM / RUN BY / DATE
GPS week: 2065   Day: 0   MJD: 58699                        COMMENT
THE COMBINED CLOCKS ARE A WEIGHTED AVERAGE OF:              COMMENT
...
    18                                                      LEAP SECONDS
     2    AR    AS                                          # / TYPES OF DATA
IGS  IGSACC @ GA and MIT                                    ANALYSIS CENTER
   229    IGS14 : IGS REALIZATION of THE ITRF2014           # OF SOLN STA / TRF
ABMF 97103M001           2919785785 -5383744963  1774604854SOLN STA NAME / NUM
ABPO 33302M001           4097216545  4429119196 -2065771184SOLN STA NAME / NUM
ADIS 31502M001           4913652571  3945922819   995383509SOLN STA NAME / NUM
...
    31                                                      # OF SOLN SATS
G01 G02 G03 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 G16 PRN LIST
G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 PRN LIST
G32                                                         PRN LIST
G                   igs14_2062.atx                          SYS / PCVS APPLIED
                                                            END OF HEADER
AR GPST 2019 08 04 00 00  0.000000  2    2.031378026801e-08  0.000000000000e+00
AR ALBH 2019 08 04 00 00  0.000000  2    2.685697915664e-08  2.647813470470e-11
...
AS G01  2019 08 04 00 00  0.000000  2   -8.616827744323e-05  3.362553644680e-11
AS G02  2019 08 04 00 00  0.000000  2   -2.750040416487e-04  2.953488394790e-11
...
```

[1] J. Ray and W. Gurtner, RINEX extensions to handle clock information, version 3.02, Sep 2010

ANTEX



ANTEX Version + Sat System

Type + Sate ID + Sat code(opt) (Sat Ant)

Start/End of Validity Period in GPST (opt)

Sat System + Freq Code

Type/Serial # (Rec Ant)

PCO (mm) in X,Y,Z (Sat Ant), N,E,U (Rec Ant)

Non-azimuth dependent PCV (mm) for each zenith/ nadir angles

```
     1.4            M                                       ANTEX VERSION / SYST
A                                                           PCV TYPE / REFANT
...                                                         COMMENT
                                                            END OF HEADER
                                                            START OF ANTENNA
BLOCK IIA           G01                 G032      1992-079A TYPE / SERIAL NO
                                             0    29-JAN-17 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  17.0   1.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
  1992    11    22     0     0    0.0000000                 VALID FROM
  2008    10    16    23    59   59.9999999                 VALID UNTIL
IGS14_2062                                                  SINEX CODE
   G01                                                      START OF FREQUENCY
    279.00      0.00   2319.50                              NORTH / EAST / UP
   NOAZI   -0.80   -0.90   -0.90   -0.80   -0.40    0.20    0.80    1.30    1.40    1.20 ...
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
    279.00      0.00   2319.50                              NORTH / EAST / UP
   NOAZI   -0.80   -0.90   -0.90   -0.80   -0.40    0.20    0.80    1.30    1.40    1.20 ...
   G02                                                      END OF FREQUENCY
   ...
                                                            END OF ANTENNA
...
                                                            START OF ANTENNA
AOAD/M_B        NONE                                        TYPE / SERIAL NO
CONVERTED           TUM                      0    29-JAN-17 METH / BY / # / DATE
     5.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
IGS14_2062                                                  SINEX CODE
   G01                                                      START OF FREQUENCY
      0.66     -0.53     59.84                              NORTH / EAST / UP
   NOAZI    0.00   -0.23   -0.91   -1.94   -3.24   -4.63   -5.98   -7.11   -7.90   -8.24 ...
     0.0    0.00   -0.26   -0.98   -2.06   -3.40   -4.85   -6.23   -7.40   -8.19   -8.51 ...
   ...
   360.0    0.00   -0.26   -0.98   -2.06   -3.40   -4.85   -6.23   -7.40   -8.19   -8.51 ...
   G01                                                      END OF FREQUENCY
   ...
                                                            END OF ANTENNA
```

Increment of Azimuth (deg)

Start/End/ Increment of Zenith (Rec Ant)/ Nadir (Sat Ant) (deg)

Header Section

Record Header

Freq 1 Section

Freq 2 Section

...

Ant Record

Azimuth dependent PCV (mm) for each zenith/ nadir angles (opt)

[1] M. Rothacher, R. Schmid and M. Chen, ANTEX: The antenna exchange format, version 1.4, Sep 2010

Interpolation of Orbit

Polynomial Interpolation by Newton and Neville's algorithm

$$x(t) = x_{i,i+n}(t) \qquad (t_i \le t \le t_{i+n})$$

$$x_{j,j}(t) = x(t_j) \qquad (i \le j \le i+n)$$

$$x_{j,k}(t) = \frac{(t_k - t)x_{j,k-1}(t) + (t - t_j)x_{j+1,k}(t)}{t_k - t_j} \qquad (i \le j < k \le i+n)$$

Example
(n = 4, i = 1)

$$\begin{tikzcd}
x_{1,1}(t)=x(t_1) \arrow[dr, dash] & & & & \\
& x_{1,2}(t) \arrow[dr, dash] & & & \\
x_{2,2}(t)=x(t_2) \arrow[ur, dash] \arrow[dr, dash] & & x_{1,3}(t) \arrow[dr, dash] & & \\
& x_{2,3}(t) \arrow[ur, dash] \arrow[dr, dash] & & x_{1,4}(t) \arrow[dr, dash] & \\
x_{3,3}(t)=x(t_3) \arrow[ur, dash] \arrow[dr, dash] & & x_{2,4}(t) \arrow[ur, dash] \arrow[dr, dash] & & x(t)=x_{1,5}(t) \\
& x_{3,4}(t) \arrow[ur, dash] \arrow[dr, dash] & & x_{2,5}(t) \arrow[ur, dash] & \\
x_{4,4}(t)=x(t_4) \arrow[ur, dash] \arrow[dr, dash] & & x_{3,5}(t) \arrow[ur, dash] & & \\
& x_{4,5}(t) \arrow[ur, dash] & & & \\
x_{5,5}(t)=x(t_5) \arrow[ur, dash] & & & &
\end{tikzcd}$$

Interpolation Error

Degree of Polynomial	Position Error (cm)				Velocity Error (cm/sec)			
	3D	Radial	Along	Cross	3D	Radial	Along	Cross
n = 5	118.12	72.10	73.84	57.48	0.415	0.253	0.260	0.202
n = 6	11.57	7.31	6.89	5.75	0.051	0.032	0.031	0.025
n = 7	1.02	0.63	0.63	0.50	0.029	0.017	0.019	0.014
n = 8	0.16	0.08	0.11	0.08	0.028	0.017	0.018	0.013
n = 9	0.13	0.05	0.11	0.05	0.028	0.017	0.018	0.013
n = 10	0.13	0.05	0.10	0.06	0.028	0.017	0.018	0.013
n = 11	0.14	0.05	0.12	0.06	0.028	0.017	0.018	0.013
n = 13	0.15	0.06	0.12	0.06	0.028	0.017	0.018	0.013

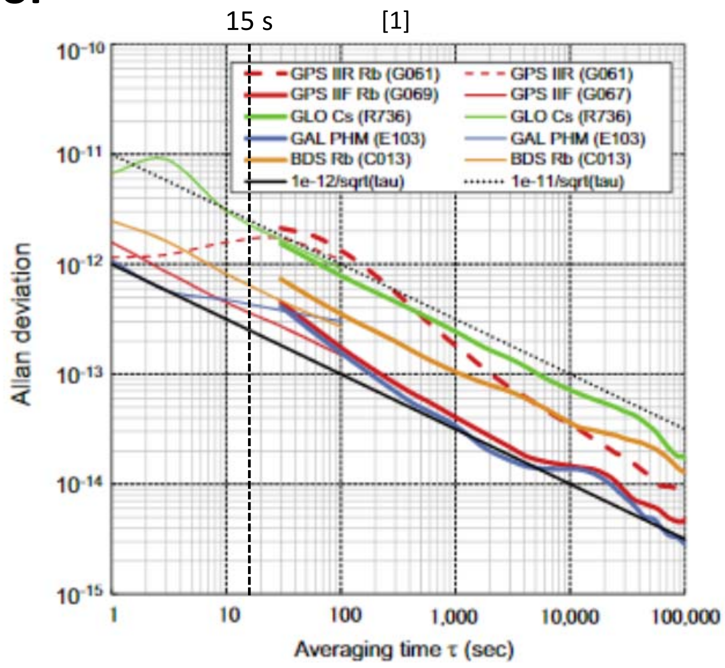
2004/10/01 24H IGS Final (GPS, interval: 15 min), average of all satellites, wrt interpolated orbit by precise orbit model

Interpolation of Clock

Linear Interpolation

$$dT^s(t) = \frac{(t_{i+1}-t)dT^s(t_i)+(t-t_i)dT^s(t_{i+1})}{t_{i+1}-t_i} \qquad (t_i \le t < t_{i+1})$$

Interpolation Error



Allan Deviation of Clock:
$4 \times 10^{-13} \sim 3 \times 10^{-12}$ @15 s

Interpolation Error
(30 s interval Clock):
$6 \times 10^{-12} \sim 4 \times 10^{-11}$ s
= 0.18 ~ 1.2 cm
(RMS)

[1] O. Montenbruck et al., The Multi-GNSS experiment (MGEX) of the international GNSS service (IGS) – achievements, prospects and challenges, Advances in Space Research, 2017

Broadcast Ephemeris

Broadcast Ephemeris and SV Clock (GPS LNAV) [1]

$$(t_{oe}, t_{oc}, IOD, \sqrt{A}, e, i_0, \Omega_0, \omega, M_0, \Delta n, \dot{I}, \dot{\Omega}, C_{us}, C_{uc}, C_{rs}, C_{rc}, C_{is}, C_{ic}, af_0, af_1, af_2)$$

Satellite Position and Clock Bias (GPS LNAV) [1]

$$t_k = t - t_{oe},\ t_c = t - t_{oc}, a = \left(\sqrt{A}\right)^2$$

$$M = M_0 + \left(\sqrt{\frac{\mu}{a^3}} + \Delta n\right) t_k$$

$$M = E - e \sin E$$

Solve Kepler equation

$$\begin{cases} E_0 = M \\ E_{i+1} = E_i - \dfrac{E_i - e \sin E_i - M}{1 - e \cos E_i} \\ E = \lim\limits_{i \to \infty} E_i \end{cases}$$

$$\nu = \mathrm{ATAN2}\left(\sqrt{1-e^2} \sin E, \cos E - e\right)$$

$$\phi = \nu + \omega$$

$$u = \phi + C_{us} \sin 2\phi + C_{uc} \cos 2\phi$$

$$r = a(1 - e \cos E) + C_{rs} \sin 2\phi + C_{rc} \cos 2\phi$$

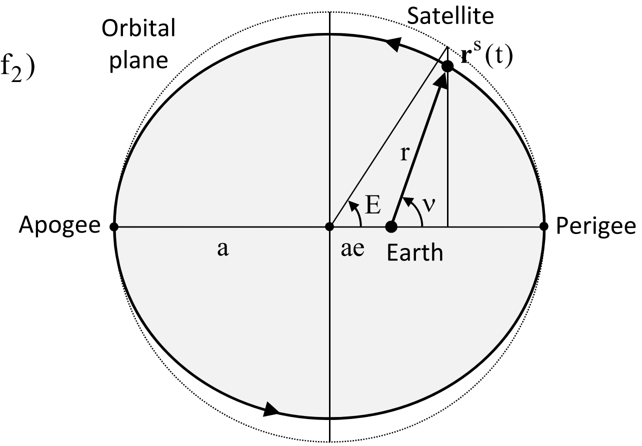
$$i = i_0 + \dot{I} t_k + C_{is} \sin 2\phi + C_{ic} \cos 2\phi$$

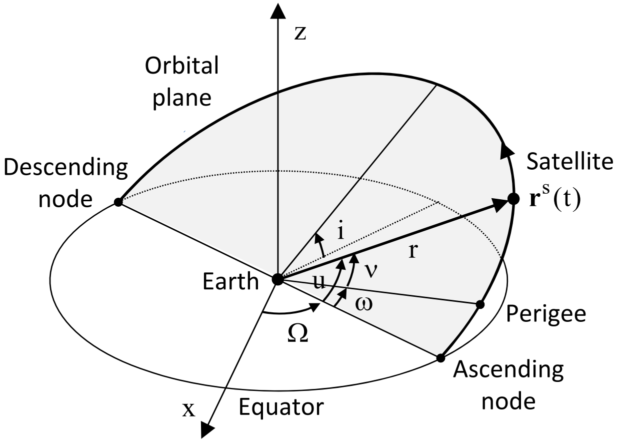
$$\Omega = \Omega_0 + (\dot{\Omega} - \omega_e)\ t_k - \omega_e\ t_{oe}$$

$$\mathbf{r}^s(t) = r \begin{pmatrix} \cos u \cos \Omega - \sin u \cos i \sin \Omega \\ \cos u \sin \Omega + \sin u \cos i \cos \Omega \\ \sin u \sin i \end{pmatrix}$$

$$dT^s(t) = af_0 + af_1 t_c + af_2 t_c{}^2 - \frac{2\sqrt{\mu}}{c^2} e \sqrt{A} \sin E$$

a : Semi-major axis
e : Eccentricity
i : Inclination
M : Mean anomaly
ω : Argument of perigee
Ω : Longitude of ascending node
E : Eccentric anomaly
ν : True anomaly
μ : Earth's gravitational constant
ω_e : Earth rotation rate





[1] IS-GPS-200K, NAVSTAR GPS space segment/navigation user segment user interfaces, Mar 2019 (20.3.3.3.3.1, 20.3.3.4.3)

SSR Orbit and Clock Corrections

SSR Orbit and Clock Corrections [1]

$$(t_0, \mathrm{IOD}, \delta O_{\mathrm{radial}}, \delta O_{\mathrm{along}}, \delta O_{\mathrm{cross}}, \delta \dot{O}_{\mathrm{radial}}, \delta \dot{O}_{\mathrm{along}}, \delta \dot{O}_{\mathrm{cross}}, C_0, C_1, C_2, C_{\mathrm{HR}})$$

Satellite Position and Clock Bias with SSR Corrections [1]

$$t_O = t_{O0} + \mathrm{UDI}_O / 2$$

$$\delta \mathbf{O} = \begin{pmatrix} \delta O_{\mathrm{radial}} \\ \delta O_{\mathrm{along}} \\ \delta O_{\mathrm{cross}} \end{pmatrix} + \begin{pmatrix} \delta \dot{O}_{\mathrm{radial}} \\ \delta \dot{O}_{\mathrm{along}} \\ \delta \dot{O}_{\mathrm{cross}} \end{pmatrix} (t - t_O)$$

$$\mathbf{r}^s(t) = \mathbf{r}^s_{\mathrm{brdc}}(t, \mathrm{IOD}) + \left(\mathbf{e}_{\mathrm{radial}}, \mathbf{e}_{\mathrm{along}}, \mathbf{e}_{\mathrm{cross}}\right) \delta \mathbf{O}$$

$$\mathbf{v}^s_{\mathrm{brdc}}(t) = \frac{\mathbf{r}^s_{\mathrm{brdc}}(t + \Delta t, \mathrm{IOD}) - \mathbf{r}^s_{\mathrm{brdc}}(t, \mathrm{IOD})}{\Delta t}$$

$$\mathbf{e}_{\mathrm{along}} = \frac{\mathbf{v}^s_{\mathrm{brdc}}(t)}{\left|\mathbf{v}^s_{\mathrm{brdc}}(t)\right|}, \quad \mathbf{e}_{\mathrm{cross}} = \frac{\mathbf{r}^s_{\mathrm{brdc}}(t, \mathrm{IOD}) \times \mathbf{v}^s_{\mathrm{brdc}}(t)}{\left|\mathbf{r}^s_{\mathrm{brdc}}(t, \mathrm{IOD}) \times \mathbf{v}^s_{\mathrm{brdc}}(t)\right|}$$

$$\mathbf{e}_{\mathrm{radial}} = \mathbf{e}_{\mathrm{along}} \times \mathbf{e}_{\mathrm{cross}}$$

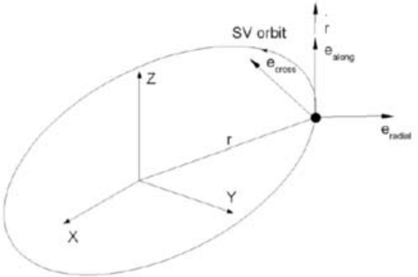
$$t_C = t_{C0} + \mathrm{UDI}_C / 2$$

$$\delta C = C_0 + C_1(t - t_C) + C_2(t - t_C)^2 + C_{\mathrm{HR}}$$

$$dT^s(t) = dT^r_{\mathrm{brdc}}(t, \mathrm{IOD}) + \frac{\delta C}{c}$$

t_{O0}, t_{C0} : Epoch time of orbit and clock corrections (s)
$\mathrm{UDI}_O, \mathrm{UDI}_C$: Update interval of orbit and clock corrections (s)
IOD : IOD indicating corresponding broadcast ephemeris
$\delta O_i, \delta \dot{O}_i,$: Satellite position/velocity corrections (m, m/s)
C_0, C_1, C_2 : Satellite clock corrections (m, m/s, m/s²)
C_{HR} : Satellite high-rate clock correction (m)
$\mathbf{r}^s_{\mathrm{brdc}}(t, \mathrm{IOD})$: Satellite position by broadcast ephemeris with IOD (m)
$\mathbf{v}^s_{\mathrm{brdc}}(t)$: Satellite velocity by broadcast ephemeris (m/s)
$dT^s_{\mathrm{brdc}}(t, \mathrm{IOD})$: Satellite clock bias by broadcast SV clock with IOD (s) *
$\delta \mathbf{O}$: Satellite orbit corrections (m)
δC : Satellite clock bias correction (m)
$\mathbf{r}^s(t)$: Satellite position with SSR corrections
$dT^s(t)$: Satellite clock bias with SSR corrections

* including relativistic correction



[1]

Figure 3.12-1. Radial, along-track and cross-track orbit components

[1] RTCM standard 10403.3, Differential GNSS (global navigation satellite system) services - version 3, Oct 2016 (3.5.13)

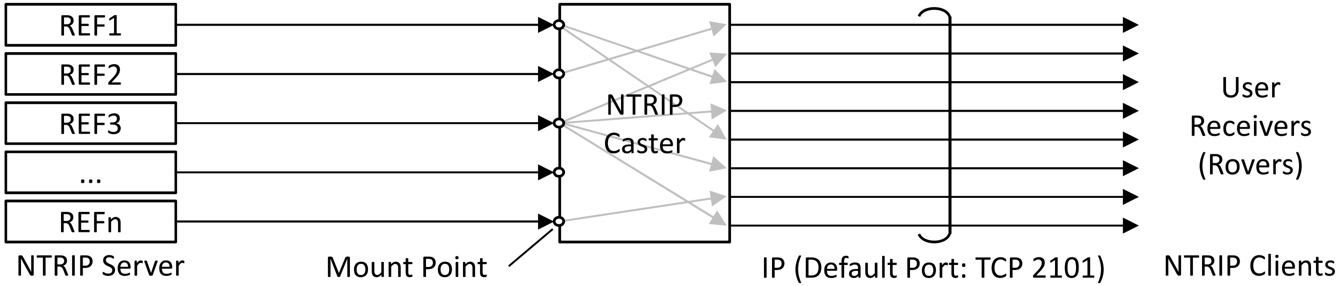
NTRIP

NTRIP (Networked Transport of RTCM via Internet Protocol) [1]

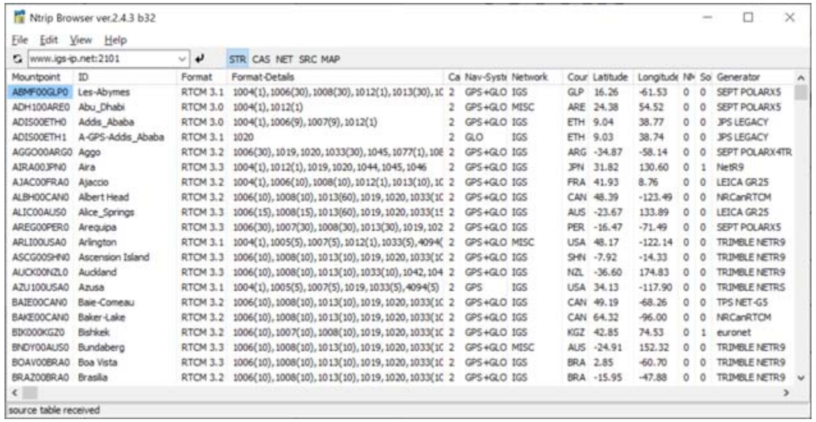
Designed based on HTTP/RTSP to disseminate DGNSS corrections and GNSS data over Internet

Ver. 1.0: Initial version only supporting TCP/IP

Ver. 2.0: Supporting RTP/UDP/IP and other feathers (chunked transfer enc., source table filtering ...)



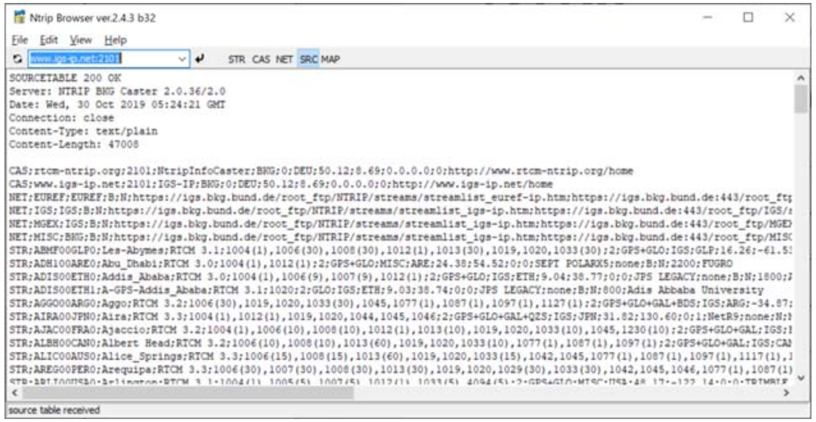
NTRIP Mount Point List



Mountpoint	ID	Format	Format-Details	Ca	Nav-Syst	Network	Cour	Latitude	Longitude	Nr	So	Generator
ABMF00GLP0	Les-Abymes	RTCM 3.1	1004(1),1006(30),1008(30),1012(1),1013(30),1C	2	GPS+GLO	IGS	GLP	16.26	-61.53	0	0	SEPT POLARX5
ADH100ARE0	Abu_Dhabi	RTCM 3.0	1004(1),1012(1)	2	GPS+GLO	MISC	ARE	24.38	54.52	0	0	SEPT POLARX5
ADIS00ETH0	Addis_Ababa	RTCM 3.0	1004(1),1006(9),1007(9),1012(1)	2	GPS+GLO	IGS	ETH	9.04	38.77	0	0	JPS LEGACY
ADIS00ETH1	A-GPS-Addis_Ababa	RTCM 3.1	1020	2	GLO	IGS	ETH	9.03	38.74	0	0	JPS LEGACY
AGGO00ARG0	Aggo	RTCM 3.2	1006(30),1019,1020,1033(30),1045,1077(1),108	2	GPS+GLO	IGS	ARG	-34.87	-58.14	0	0	SEPT POLARX4TR
AIRA00JPN0	Aira	RTCM 3.3	1004(1),1012(1),1019,1020,1044,1045,1046	2	GPS+GLO	IGS	JPN	31.82	130.60	0	1	NetR9
AJAC00FRA0	Ajaccio	RTCM 3.2	1004(1),1006(10),1008(10),1012(1),1013(10),1C	2	GPS+GLO	IGS	FRA	41.93	8.76	0	0	LEICA GR25
ALBH00CAN0	Albert Head	RTCM 3.2	1006(10),1008(10),1013(60),1019,1020,1033(1C	2	GPS+GLO	IGS	CAN	48.39	-123.49	0	0	NRCanRTCM
ALIC00AUS0	Alice_Springs	RTCM 3.3	1006(15),1008(15),1013(60),1019,1020,1033(1!	2	GPS+GLO	IGS	AUS	-23.67	133.89	0	0	LEICA GR25
AREG00PER0	Arequipa	RTCM 3.3	1006(30),1007(30),1008(30),1013(30),1019,102	2	GPS+GLO	IGS	PER	-16.47	-71.49	0	0	SEPT POLARX5
ARLI00USA0	Arlington	RTCM 3.1	1004(1),1005(5),1007(5),1012(1),1033(5),4094(	2	GPS+GLO	MISC	USA	48.17	-122.14	0	0	TRIMBLE NETR9
ASCG00SHN0	Ascension Island	RTCM 3.3	1006(10),1008(10),1013(10),1019,1020,1033(1C	2	GPS+GLO	IGS	SHN	-7.92	-14.33	0	0	TRIMBLE NETR9
AUCK00NZL0	Auckland	RTCM 3.3	1006(10),1008(10),1013(10),1033(10),1042,104	2	GPS+GLO	IGS	NZL	-36.60	174.83	0	0	TRIMBLE NETR9
AZU100USA0	Azusa	RTCM 3.1	1004(1),1005(5),1007(5),1019,1033(5),4094(5)	2	GPS	IGS	USA	34.13	-117.90	0	0	TRIMBLE NETRS
BAIE00CAN0	Baie-Comeau	RTCM 3.2	1006(10),1008(10),1013(10),1019,1020,1033(1C	2	GPS+GLO	IGS	CAN	49.19	-68.26	0	0	TPS NET-G5
BAKE00CAN0	Baker-Lake	RTCM 3.2	1006(10),1008(10),1013(10),1019,1020,1033(1C	2	GPS+GLO	IGS	CAN	64.32	-96.00	0	0	NRCanRTCM
BIK000KGZ0	Bishkek	RTCM 3.2	1006(10),1007(10),1008(10),1019,1020,1033(1C	2	GPS+GLO	IGS	KGZ	42.85	74.53	0	1	euronet
BNDY00AUS0	Bundaberg	RTCM 3.3	1006(10),1008(10),1013(10),1019,1020,1033(1C	2	GPS+GLO	MISC	AUS	-24.91	152.32	0	0	TRIMBLE NETR9
BOAV00BRA0	Boa Vista	RTCM 3.3	1006(10),1008(10),1013(10),1019,1020,1033(1C	2	GPS+GLO	IGS	BRA	2.85	-60.70	0	0	TRIMBLE NETR9
BRAZ00BRA0	Brasilia	RTCM 3.2	1006(10),1008(10),1013(10),1019,1020,1033(1C	2	GPS+GLO	IGS	BRA	-15.95	-47.88	0	0	TRIMBLE NETR9

source table received

NTRIP Source Table



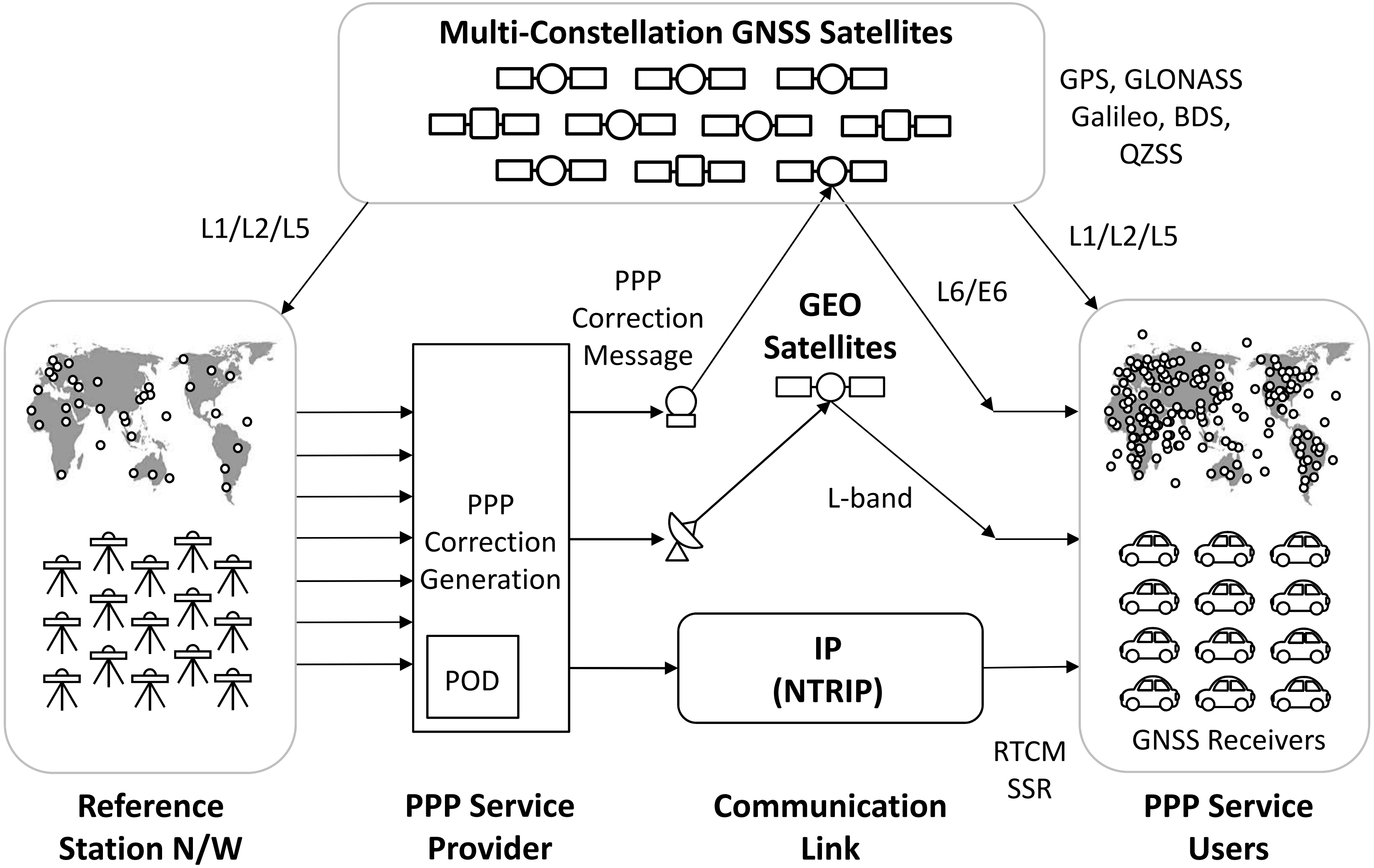
```
SOURCETABLE 200 OK
Server: NTRIP BKG Caster 2.0.36/2.0
Date: Wed, 30 Oct 2019 05:24:21 GMT
Connection: close
Content-Type: text/plain
Content-Length: 47008

CAS;rtcm-ntrip.org;2101;NtripInfoCaster;BKG;0;DEU;50.12;8.69;0.0.0.0;0;http://www.rtcm-ntrip.org/home
CAS;www.igs-ip.net;2101;IGS-IP;BKG;0;DEU;50.12;8.69;0.0.0.0;0;http://www.igs-ip.net/home
NET;EUREF;EUREF;B;N;https://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_euref-ip.htm;https://igs.bkg.bund.de:443/root_ft
NET;IGS;IGS;B;N;https://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_igs-ip.htm;https://igs.bkg.bund.de:443/root_ftp/IGS/
NET;MGEX;IGS;B;N;https://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_igs-ip.htm;https://igs.bkg.bund.de:443/root_ftp/MGE
NET;MISC;BKG;B;N;https://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_igs-ip.htm;https://igs.bkg.bund.de:443/root_ftp/MIS
STR;ABMF00GLP0;Les-Abymes;RTCM 3.1;1004(1),1006(30),1008(30),1012(1),1013(30),1019,1020,1033(30);2;GPS+GLO;IGS;GLP;16.26;-61.5
STR;ADH100ARE0;Abu_Dhabi;RTCM 3.0;1004(1),1012(1);2;GPS+GLO;MISC;ARE;24.38;54.52;0;0;SEPT POLARX5;none;B;N;2200;FUGRO
STR;ADIS00ETH0;Addis_Ababa;RTCM 3.0;1004(1),1006(9),1007(9),1012(1);2;GPS+GLO;IGS;ETH;9.04;38.77;0;0;JPS LEGACY;none;B;N;1800;
STR;ADIS00ETH1;A-GPS-Addis_Ababa;RTCM 3.1;1020;2;GLO;IGS;ETH;9.03;38.74;0;0;JPS LEGACY;none;B;N;800;Adis Abbaba University
STR;AGGO00ARG0;Aggo;RTCM 3.2;1006(30),1019,1020,1033(30),1045,1077(1),1087(1),1097(1),1127(1);2;GPS+GLO+GAL+BDS;IGS;ARG;-34.87;
STR;AIRA00JPN0;Aira;RTCM 3.3;1004(1),1012(1),1019,1020,1044,1045,1046;2;GPS+GLO+GAL+QZS;IGS;JPN;31.82;130.60;0;1;NetR9;none;N;
STR;AJAC00FRA0;Ajaccio;RTCM 3.2;1004(1),1006(10),1008(10),1012(1),1013(10),1019,1020,1033(10),1045,1230(10);2;GPS+GLO+GAL;IGS;
STR;ALBH00CAN0;Albert Head;RTCM 3.2;1006(10),1008(10),1013(60),1019,1020,1033(10),1077(1),1087(1),1097(1);2;GPS+GLO+GAL;IGS;CA
STR;ALIC00AUS0;Alice_Springs;RTCM 3.3;1006(15),1008(15),1013(60),1019,1020,1033(15),1042,1045,1077(1),1087(1),1097(1),1117(1),
STR;AREG00PER0;Arequipa;RTCM 3.3;1006(30),1007(30),1008(30),1013(30),1019,1020,1029(30),1033(30),1042,1045,1046,1077(1),1087(1)
STR;ARLI00USA0;Arlington;RTCM 3.1;1004(1),1005(5),1007(5),1012(1),1033(5),4094(5);2;GPS+GLO;MISC;USA;48.17;-122.14;0;0;TRIMBLE
```

source table received

[1] RTCM standard 10410.1 with amendment 1, Networked transport of RTCM via internet protocol (Ntrip) - version 2.0, June 2011

PPP Service Architecture



QZSS L6 (1/2)

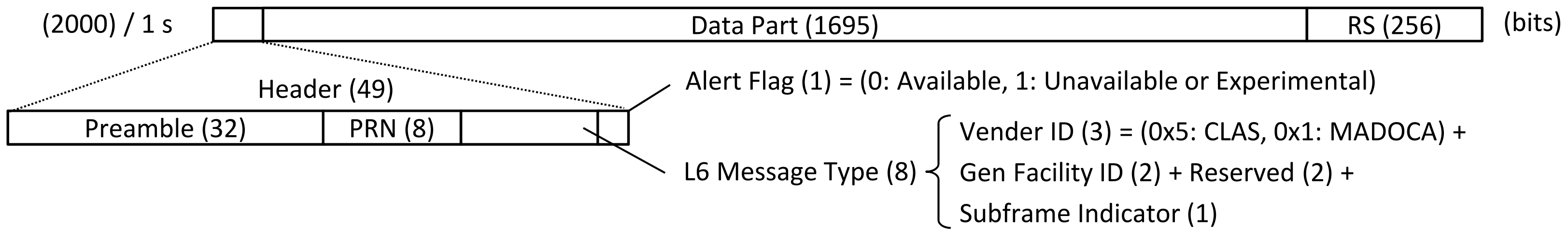
QZSS L6 Signal Specifications

Satellite	QZS-1 (Block I)		QZS-2, 3, 4 (Block II)	
Carrier Frequency	1278.75 MHz		1278.75 MHz	
Modulation	BPSK(5), TDM		BPSK(5), TDM	
Min Received Power	- 155.7 dBW		- 156.82 dBW	
Component	Data	Pilot	Data	Data
PRN number	193	193	194 ~ 197 (QZO) 199 ~ 201 (GEO)	204 ~ 207 (QZO) 209 ~ 211 (GEO)
Chip Rate	2.5575 Mcps	2.5575 Mcps	2.5575 Mcps	2.5575 Mcps
Code Length	4 ms	410 ms	4 ms	4 ms
Data	L6D	-	L6D	L6E
Data Modulation	CSK (8 bit/sym)	-	CSK (8 bit/sym)	CSK (8 bit/sym)
Symbol Rate	250 sym/s		250 sym/s	250 sym/s
Data Rate	2 kbps	-	2 kbps	2 kbps
Frame Length	2000 bits		2000 bits	2000 bits
Frame Rate	1 frame/s	-	1 frame/s	1 frame/s
FEC	RS(255,223)	-	RS(255,223)	RS(255,223)
Contents	CLAS	-	CLAS	MADOCA
Status	Available (2018/11/1~)	-	Available (2018/11/1~)	Experimental (2019/10)

IS-QZSS-L6-001, Quasi-Zenith Satellite System Interface Specification Centimeter Level Augmentation Service, Nov 5, 2018

QZSS L6 (2/2)

QZSS L6 L6D, L6E Frame



(2000) / 1 s

Data Part (1695)

RS (256)

(bits)

Header (49)

Preamble (32)

PRN (8)

Alert Flag (1) = (0: Available, 1: Unavailable or Experimental)

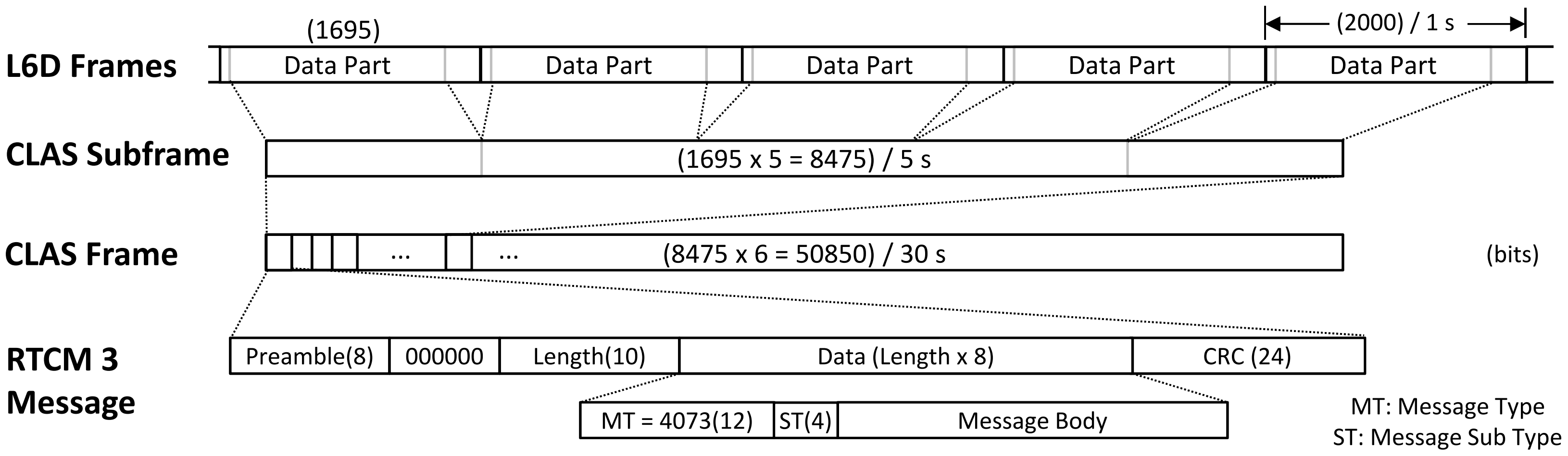
L6 Message Type (8)

Vender ID (3) = (0x5: CLAS, 0x1: MADOCA) +
Gen Facility ID (2) + Reserved (2) +
Subframe Indicator (1)

	CLAS	**MADOCA**
Positioning Mode	PPP-RTK	PPP
Service Area	Japanese Island	All areas covered by QZSS
Accuracy	H: < 6 cm, V: < 12 cm (static, 95%) H: < 12 cm, V: < 24 cm (kinematic, 95%)	Not Specified
TTFF/Convergence Time	< 60 s (95%)	Not Specified
Target GNSS (Signals) *1	GPS (L1C/A, L2P(Y), L2C, L5), GAL (E1, E5a), QZS (L1C/A, L2C, L5)	GPS (L1C/A, L2P(Y)), GLO (L1C/A, L2P), QZS-1 (?)
Corrections	Mask, Orbit Correction, Clock Correction, Code Bias, Phase Bias, URA, STEC Correction, Gridded Correction	Orbit Correction, High-Rate Clock Correction, Code Bias, URA
Format	Compact SSR (CSSR) on RTCM 3 Proprietary (MT 4073)	RTCM 3 SSR + Draft SSR (w/o preamble, length, CRC)

*1 in October 2019

Compact SSR (CSSR)



L6D Frames

(1695)

Data Part | Data Part | Data Part | Data Part | Data Part

(2000) / 1 s

CLAS Subframe

(1695 x 5 = 8475) / 5 s

CLAS Frame

… … (8475 x 6 = 50850) / 30 s

(bits)

RTCM 3 Message

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

MT = 4073(12) | ST(4) | Message Body

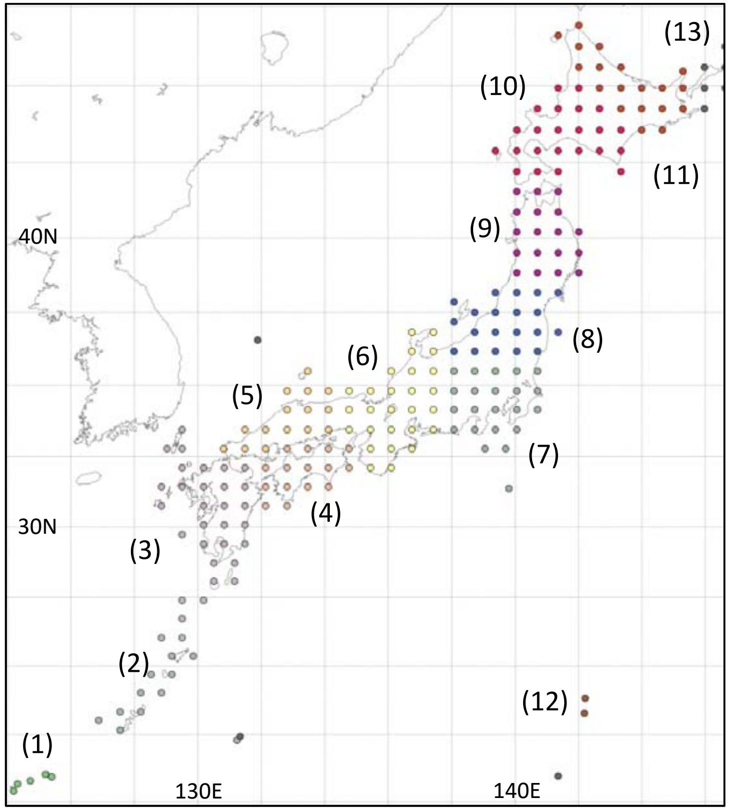
MT: Message Type
ST: Message Sub Type

RTCM 3 Message	MT	ST	Contents
Compact SSR Mask	4073	1	Satellite Mask, Cell Mask, Signal Mask
Compact SSR Orbit Corrections	4073	2	IODE, Delta-Orbit (Radial, Along-Track, Cross-Track)
Compact SSR Clock Corrections	4073	3	Delta-Clock C0
Compact SSR Code Bias	4073	4	Code Bias
Compact SSR Phase Bias	4073	5	Phase Bias, Phase Discount. Indicator.
Compact SSR Code and Phase Bias	4073	6	Code Bias, Phase Bias, Phase Discount. Indicator, (N/W ID, N/W SV Mask)
Compact SSR URA	4073	7	URA
Compact SSR STEC Correction	4073	8	STEC Quality Indicator, Polynomial Coefficients, N/W ID, N/W SV Mask
Compact SSR Gridded Correction	4073	9	(Tropos. Hydro-Static Vertical Delay, Tropos. Wet Vertical Delay), STEC Residual Correction, N/W ID, N/W SV Mask, # of Grids
CLAS Service Information	4073	10	TBD
Compact SSR GNSS Combined Correction	4073	11	IODE, Delta-Orbit (Radial, Along-Track, Cross-Track), Delta-Clock C0

[1] IS-QZSS-L6-001 Quasi-Zenith Satellite System Interface Specification Centimeter Level Augmentation Service, November 5, 2018

CSSR Networks and Grids

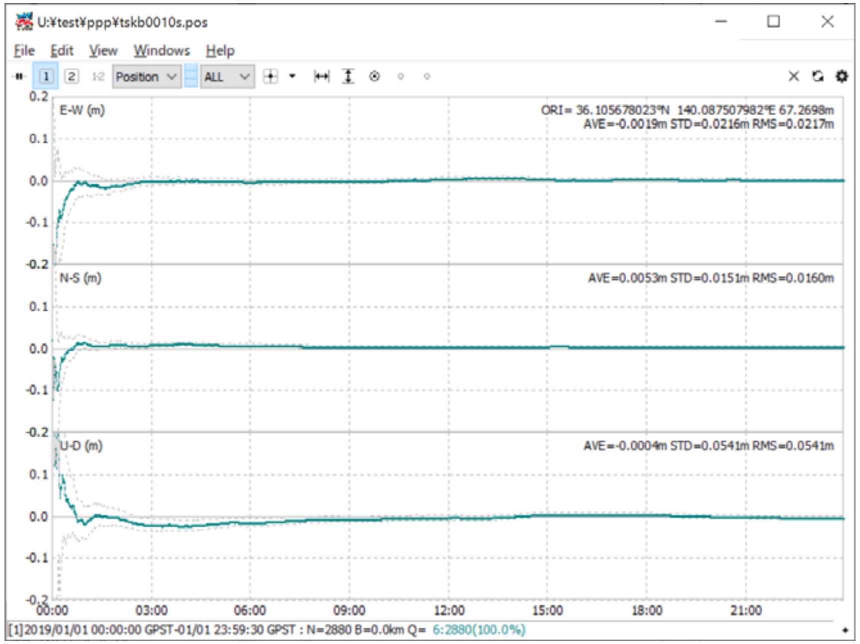
N/W ID	N/W	# of Grids	Area	
			Latitude (deg)	Longitude (deg)
1	Ishigaki	8	24.06 - 24.83 N	122.94 - 125.37 E
2	Okinawa	11	25.83 - 28.30 N	126.87 - 131.23 E
3	Kyusyu	32	28.84 - 34.77 N	128.84 - 131.47 E
4	Shikoku	15	32.62 - 34.23 N	132.13 - 134.76 E
5	Chugoku	15	34.23 - 36.39 N	130.82 - 134.11 E
6	Kansai	27	34.23 - 37.47 N	134.76 - 137.40 E
7	Kanto	22	33.11 - 36.39 N	138.05 - 140.69 E
8	Tohoku South	20	36.93 - 38.55 N	138.05 - 141.34 E
9	Tohoku North	18	39.09 - 41.24 N	140.03 - 142.00 E
10	Hokkaido West	23	41.78 - 43.94 N	139.37 - 143.32 E
11	Hokkaido East	19	42.86 - 45.55 N	141.34 - 145.29 E
12	Ogasawara	2	26.64 - 27.07 N	142.16 - 142.20 E
13	Hokkaido Island	13	43.40 - 45.55 N	145.95 - 149.24 E
14	Island	1	37.24 N	131.87 E
15	Island	1	25.96 N	131.31 E
16	Island	1	25.73 N	123.54 E
17	Island	1	24.77 N	141.34 E
18	Island	1	24.28 N	153.99 E
19	Island	1	20.44 N	136.09 E



[1] IS-QZSS-L6-001 Quasi-Zenith Satellite System Interface Specification Centimeter Level Augmentation Service, November 5, 2018

PPP Solution Example

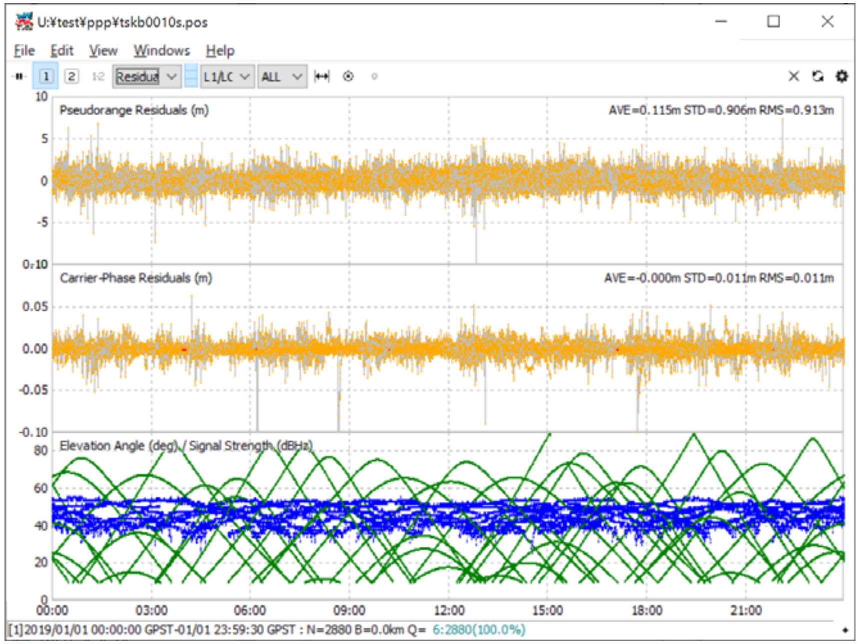
Static PPP Solutions



```
ORI= 36.105678023°N 140.087507982°E 67.2698m
AVE=-0.0019m STD=0.0216m RMS=0.0217m
AVE=0.0053m STD=0.0151m RMS=0.0160m
AVE=-0.0004m STD=0.0541m RMS=0.0541m
[1]2019/01/01 00:00:00 GPST-01/01 23:59:30 GPST : N=2880 B=0.0km Q= 6:2880(100.0%)
```

Station Position Error: E 2.2 mm, N 4.2 mm, U 3.4 mm
(wrt IGS Final SINEX)

Static PPP Residuals



```
AVE=0.115m STD=0.906m RMS=0.913m
AVE=-0.000m STD=0.011m RMS=0.011m
[1]2019/01/01 00:00:00 GPST-01/01 23:59:30 GPST : N=2880 B=0.0km Q= 6:2880(100.0%)
```

Residuals RMS: Code 91 cm, Phase 1.1 cm
(Iono-free LC)

Station: IGS TSKB, Time: 2019/01/01 00:00:00-23:59:30 GPST (24 H),
PPP S/W: RTKPOST 2.4.3 b33, Ephemeris: IGS Final Orbit/Clock (30s)

PPP Options: Positioning Mode: PPP-Static, Frequencies: L1+L2, Filter Type: Forward, Elevation Mask: 10 deg, Earth Tide Correction: Solid, Ionosphere Correction: Iono-Free LC, Troposphere-Correction: Estimate ZTD, Satellite Ephemeris/Clock: Precise, Sat PCV/Rec PCV/PhWU: ON, GNSS: GPS, Statistics: Code/Carrier-phase error ratio: 100/100, Carrier-phase error a+b/sinEl (m): 0.003/0.003, Process Noise (1-sigma/sqrt(s)): Carrier phase bias 1E-4 cyc, Zenith Tropospheric Delay 1E-4 m, Antenna Type: *(Auto), Satellite/Receiver Antenna PCV: igs14.atx, DCB Data: P1C11901.DCB)

Appendix

GNSS Signals (1/3)

System	Carrier Freq (MHz)	Signal	I/Q	Min Received Power (dBW)	Modulation	Spreading Code				Navigation Data			Notes
						Length (chips)	Chip Rate (Mcps)	Overlay Code (chips)	Period (ms)	Data	Bit Rate (bps)	FEC	
GPS [1][2]	1575.42	L1C/A	Q	-158.5	BPSK(1)	1023	1.023	-	1	LNAV	50	-	
		L1P(Y)^{*1}	I	-161.5	BPSK(10)	1week	10.23	-	?	LNAV	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	50	1/2	GPS III~
		L1C-P	I	-158.25	TMBOC(6,1,4/33)	10230	1.023	1800	18000	-	-	-	
	1227.6	L2C/A	Q	-164.5	BPSK(1)	1023	1.023	-	1	LNAV	50	-	Block IIR-M~
		L2P(Y)^{*1}	I	-164.5/-161.5	BPSK(10)	1week	10.23	-	?	LNAV	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	-	Block IIR-M~
										CNAV	25	1/2	
		L2C-L				767250	0.5115	-	1500	-	-	-	
	1176.45	L5-I	I	-157.9/-157.0	BPSK(10)	10230	10.23	10 (NH)	10	CNAV	50	1/2	Block IIF~
		L5-Q	Q	-157.9/-157.0	BPSK(10)	10230	10.23	20 (NH)	20	-	-	-	
GLONASS [3][4][5][6]	1602.0 + 0.5625K^{*2}	L1C/A	I	-161.0	BPSK	511	0.511	-	1	NAV	50	-	
		L1P	Q	?	BPSK	5110000	5.11	-	1000	?	?	-	
	1600.995	L1OCd	Q	?	BPSK(1), TDM	1023	0.5115	2	4	NAV	125	1/2	GLO-K2~
		L1OCp				4092	2.046	4 (MS)	8	-	-	-	
	1246.0 + 0.4375K^{*2}	L2C/A	I	-167.0	BPSK	511	0.511	-	1	NAV	50	-	
		L2P	Q	?	BPSK	5110000	5.11	-	1000	?	?	-	
	1248.06	L2CSI	Q	?	BPSK(1), TDM	?	0.5115	?	?	?	?	?	GLO-K2~
		L2OCp				10230	0.5115	50	1000	-	-	-	
	1202.025	L3OCd	I	?	BPSK(10)	10230	10.23	5 (BC)	5	NAV	100	1/2	GLO-K1~
		L3OCp	Q	?	BPSK(10)	10230	10.23	10 (NH)	10	-	-	-	

*1 AS ON, *2 K = {-7 ... +6}

[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] GLONASS interface control document - navigation radiosignal in bands L1, L2, version 5.1, 2008, [4] GLONASS interface control document - code division multiple access open service navigation signal in L1 frequency band, edition 1.0, 2016, [5] GLONASS interface control document - code division multiple access open service navigation signal in L2 frequency band, edition 1.0, 2016, [6] GLONASS interface control document - code division multiple access open service navigation signal in L3 frequency band, edition 1.0, 2016

GNSS Signals (2/3)

System	Carrier Freq (MHz)	Signal	I/Q	Min Received Power (dBW)	Modulation	Spreading Code				Navigation Data			Notes
						Length (chips)	Chip Rate (Mcps)	Overlay Code (chips)	Period (ms)	Data	Bit Rate (bps)	FEC	
Galileo [7]	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	125	1/2	OS, SoL, CS
		E1-C	Q		CBOC(6,1,1/11)	4092	1.023	25	100	-	-	-	
	1176.45	E5a-I	I	-155.0	BPSK(10)	10230	10.23	20	20	F/NAV	50	1/2	OS, CS
		E5a-Q	Q		BPSK(10)	10230	10.23	100	100	-	-	-	
	1207.14	E5b-I	I	-155.0	BPSK(10)	10230	10.23	4	4	I/NAV	125	1/2	OS, SoL, CS
		E5b-Q	Q		BPSK(10)	10230	10.23	100	100	-	-	-	
	1191.795	E5a+b*3	-	(-152.0)	8-PSK(10)	10230	10.23	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	500	1/2	CS, HAS
		E6-C	Q		BPSK(5)	5115	5.115	100	100	-	-	-	
QZSS [8][9][10][11]	1575.42	L1C/A	I/Q	-158.5*4	BPSK(1)	1023	1.023	-	1	LNAV	50	-	
		L1C-D	I	-163.0*5	BOC(1,1)	10230	1.023	-	10	CNAV2	50	1/2	
		L1C-P	Q	-158.25	BOC(1,1)	10230	1.023	1800	18000	-	-	-	Block I
			I	-158.25*6	TMBOC(6,1,4/33)	10230	1.023	1800	18000	-	-	-	Block II
		L1S	I	-161.0/-158.5	BPSK(1)	1023	1.023	-	1	L1S	250	1/2	SLAS
	1227.6	L2C-M	I	-160.0/-158.5	BPSK(1), TDM	10230	0.5115	-	20	CNAV	25	1/2	
		L2C-L				767250	0.5115	-	1500	-	-	-	
	1176.45	L5-I	I	-157.9/-157.0	BPSK(10)	10230	10.23	10 (NH)	10	CNAV	50	1/2	
		L5-Q	Q	-157.9/-157.0	BPSK(10)	10230	10.23	20 (NH)	20	-	-	-	
		L5S-I	I	-157.0*7	BPSK(10)	10230	10.23	10 (NH)	10	L5S	250	1/2	
		L5S-Q	Q		BPSK(10)	10230	10.23	20 (NH)	20	-	-	-	
	1278.75	L6	I	-155.7	BPSK(5), TDM	10230	2.5575	-	4	L6D	2000	RS	
						1048575	2.5575	-	410	-	-	-	Block I
						10230	2.5575	-	4	L6E	2000	RS	Block II

*3 AltBOC *4 -164.0 dBW (SVID=7), *5 -167.2 dBW (SVID=7), *6 -162.4 dBW (SVID=7), *7 -162.6 dBW (SVID=3)

[7] European GNSS (Galileo) open service signal-in-space interface control document (OS SIS ICD), Issue 1, Revision 3, 2016, [8] Quasi-Zenith satellite system interface specification - satellite positioning, navigation and timing service (IS-QZSS-PNT-003), 2018, [9] Quasi-zenith satellite system interface specification - sub-meter level augmentation service (IS-QZSS-L1S-003), 2018, [10] Quasi-zenith satellite system interface specification - centimeter level augmentation service (IS-QZSS-L6-003), 2018, [11] Quasi-zenith satellite system interface specification - positioning technology verification service (IS-QZSS-TV-002), 2018,

GNSS Signals (3/3)

System	Carrier Freq (MHz)	Signal	I/Q	Min Received Power (dBW)	Modulation	Spreading Code				Navigation Data			Notes
						Length (chips)	Chip Rate (Mcps)	Overlay Code (chips)	Period (ms)	Data	Bit Rate (bps)	FEC	
BeiDou [12][13][14][15]	1561.098	B1I	I	-163.0	BPSK(2)	2046	2.046	20 (NH)	20	D1*10	50	BCH	BDS-2*12
								-	1	D2*11	500	BCH	
		B1Q	Q	?	BPSK(2)	?	2.046	?	?	?	?	?	
	1575.42	B1C-D	I	-159.0/-161.0	BOC(1,1)	10230	1.023	-	10	B-CNAV1	50	1/2	BDS-3
		B1C-P	Q		QMBOC(6,1,4/33)	10230	1.023	1800	18000	-	-	-	
		B1A-D*8	I	?	BOC(14,2)	?	?	?	?	?	50	?	
		B1A-P*8	Q			?	?	?	?	-	-	-	
	1207.14	B2I	I	?	BPSK(2)	2046	2.046	20 (NH)	20	D1*10	50	BCH	BDS-2
								-	1	D2*11	500	BCH	
		B2Q*8	Q	?	BPSK(10)	10230	10.23	?	?	?	?	?	
	1176.45	B2a-D	I	-156.0/-158.0	BPSK(10)	10230	10.23	5	5	B-CNAV2	25	1/2	BDS-3
		B2a-P	Q		BPSK(10)	10230	10.23	100	100	-	-	-	
	1207.14	B2b-I	I	?	BPSK(10)	10230	10.23	?	?	?	500	-	
		B2b-Q	Q	?	BPSK(10)	10230	10.23	?	?	?	500	-	
	1191.795	B2a+b*9	-	?	8-PSK(10)	10230	10.23	?	?	-	-	-	
	1268.52	B3I	I	-163.0	BPSK(10)	10230	10.23	-	1	D1*10	50	BCH	BDS-2*12
										D2*11	500	BCH	
		B3Q*8	Q	?	BPSK(10)	?	10.23	?	?	?	?	?	
		B3A-D*8	I	?	BPSK(10)	?	10.23	?	?	?	50	?	BDS-3
		B3A-P*8	Q		BPSK(10)	?	10.23	?	?	-	-	-	
SBAS	1575.42	L1C/A	I	-	BPSK(1)	1023	1.023	-	1	SBAS	250	1/2	
	1176.45	L5-I	I	-	BPSK(10)	10230	10.23	10 (NH)	10	SBAS	250	1/2	
		L5-Q	Q	-	BPSK(10)	10230	10.23	20 (NH)	20	-	-	-	

*8 Authorized signal, *9 ACE-BOC, *10 IGSO/MEO satellites, *11 GEO satellites *12 B1I and B3I signals are also transmitted by BDS-3

[12] BeiDou navigation satellite system signal in space interface control document - open service signal B1I, version 3, 2019, [13] BeiDou navigation satellite system signal in space interface control document - open service signal B1C, version 1.0, 2017, [14] BeiDou navigation satellite system signal in space interface control document - open service signal B2a, version 1.0, 2017, [15] BeiDou navigation satellite system signal in space interface control document - open service signal B3I, version 1.0, 2018

GNSS Signal ID (1/4)

System	Carrier Frequency (MHz)	Channel or Code	RINEX *								RTCM3 MSM[9]	BINEX[10]
			2.10[1]	2.11[2]	2.12[3]	3.00[4]	3.01[5]	3.02[6]	3.03[7]	3.04[8]		
GPS	L1/ 1575.42	C/A	C1	C1	CA	1C	1C	1C	1C	1C	2	1
		L1C(D)	-	-	CB	1S	1S	1S	1S	1S	30	6
		L1C(P)	-	-	CB	1L	1L	1L	1L	1L	31	6
		L1C(D+P)	-	-	CB	1X	1X	1X	1X	1X	32	6
		P (AS off)	P1	P1	P1	1P	1P	1P	1P	1P	3	2
		Z-tracking and similar (AS on)	P1	P1	P1	1W	1W	1W	1W	1W	4	3
		Y	-	-	-	1Y	1Y	1Y	1Y	1Y	-	4
		M	-	-	-	1M	1M	1M	1M	1M	-	5
		codeless	-	-	-	1N	1N	1N	1N	1N	-	7
	L2/ 1227.60	C/A	-	-	-	2C	2C	2C	2C	2C	8	11
		L1(C/A)+(P2-P1) (semi-codeless)	P2	P2	C2	2D	2D	2D	2D	2D	-	12
		L2C(M)	-	C2	CC	2S	2S	2S	2S	2S	15	13
		L2C(L)	-	C2	CC	2L	2L	2L	2L	2L	16	14
		L2C(M+L)	-	C2	CC	2X	2X	2X	2X	2X	17	15
		P (AS off)	P2	P2	P2	2P	2P	2P	2P	2P	9	16
		Z-tracking and similar (AS on)	P2	P2	P2	2W	2W	2W	2W	2W	10	17
		Y	-	-	-	2Y	2Y	2Y	2Y	2Y	-	18
		M	-	-	-	2M	2M	2M	2M	2M	-	19
		codeless	-	-	-	2N	2N	2N	2N	2N	-	20
	L5/ 1176.45	I	-	C5	C5	5I	5I	5I	5I	5I	22	24
		Q	-	C5	C5	5Q	5Q	5Q	5Q	5Q	23	25
		I+Q	-	C5	C5	5X	5X	5X	5X	5X	24	26
GLONASS	G1/ 1602+K*9/16	C/A	C1	C1	CA	1C	1C	1C	1C	1C	2	1
		P	P1	P1	P1	1P	1P	1P	1P	1P	3	2
	G1a/ 1600.995	L1OCd	-	-	-	-	-	-	-	4A	-	-
		L1OCp	-	-	-	-	-	-	-	4B	-	-
		L1OCd+L1OCp	-	-	-	-	-	-	-	4X	-	-

GNSS Signal ID (2/4)

System	Carrier Frequency (MHz)	Channel or Code	RINEX *								RTCM3 MSM[9]	BINEX[10]
			2.10[1]	2.11[2]	2.12[3]	3.00[4]	3.01[5]	3.02[6]	3.03[7]	3.04[8]		
GLONASS (cont.)	G2/ 1246+K*7/16	C/A (GLONASS-M)	-	C2	CD	2C	2C	2C	2C	2C	8	11
		P	P2	P2	P2	2P	2P	2P	2P	2P	9	12
	G2a/ 1248.06	L2CSI	-	-	-	-	-	-	-	6A	-	-
		L2OCp	-	-	-	-	-	-	-	6B	-	-
		L2CSI+L2OCp	-	-	-	-	-	-	-	6X	-	-
	G3/ 1202.025	I	-	-	-	-	-	3I	3I	3I	-	14
		Q	-	-	-	-	-	3Q	3Q	3Q	-	15
		I+Q	-	-	-	-	-	3X	3X	3X	-	16
Galileo	E1/ 1575.42	A PRS	-	C1	C1	1A	1A	1A	1A	1A	3	1
		B I/NAV OS/CS/SoL	-	C1	C1	1B	1B	1B	1B	1B	4	2
		C	-	C1	C1	1C	1C	1C	1C	1C	2	3
		B+C	-	C1	C1	1X	1X	1X	1X	1X	5	4
		A+B+C	-	C1	C1	1Z	1Z	1Z	1Z	1Z	6	5
	E5a/ 1176.45	I F/NAV OS	-	C5	C5	5I	5I	5I	5I	5I	22	7
		Q no data	-	C5	C5	5Q	5Q	5Q	5Q	5Q	23	8
		I+Q	-	C5	C5	5X	5X	5X	5X	5X	24	9
	E5b/ 1207.14	I I/NAV OS/CS/SoL	-	C7	C7	7I	7I	7I	7I	7I	14	11
		Q no data	-	C7	C7	7Q	7Q	7Q	7Q	7Q	15	12
		I+Q	-	C7	C7	7X	7X	7X	7X	7X	16	13
	E5a+b/ 1191.795	I	-	C8	C8	8I	8I	8I	8I	8I	18	15
		Q	-	C8	C8	8Q	8Q	8Q	8Q	8Q	19	16
		I+Q	-	C8	C8	8X	8X	8X	8X	8X	20	17
	E6/ 1278.75	A PRS	-	C6	C6	6A	6A	6A	6A	6A	9	19
		B C/NAV CS	-	C6	C6	6B	6B	6B	6B	6B	10	20
		C no data	-	C6	C6	6C	6C	6C	6C	6C	8	21
		B+C	-	C6	C6	6X	6X	6X	6X	6X	11	22
		A+B+C	-	C6	C6	6Z	6Z	6Z	6Z	6Z	12	23

GNSS Signal ID (3/4)

System	Carrier Frequency (MHz)	Channel or Code	RINEX *								RTCM3 MSM[9]	BINEX[10]
			2.10[1]	2.11[2]	2.12[3]	3.00[4]	3.01[5]	3.02[6]	3.03[7]	3.04[8]		
BeiDou	B1-2/ 1561.098	I	-	-	C2	-	2I	1I	2I	2I	2	1
		Q	-	-	C2	-	2Q	1Q	2Q	2Q	3	2
		I+Q	-	-	C2	-	2X	1X	2X	2X	4	3
	B1/ 1575.42 (BDS-3)	Data	-	-	-	-	-	-	-	1D	-	13
		Pilot	-	-	-	-	-	-	-	1P	-	14
		Data+Pilot	-	-	-	-	-	-	-	1X	-	15
		B1A	-	-	-	-	-	-	-	1A	-	-
		Codeless	-	-	-	-	-	-	-	1N	-	-
	B2a/ 1176.45 (BDS-3)	Data	-	-	-	-	-	-	-	5D	-	17
		Pilot	-	-	-	-	-	-	-	5P	-	18
		Data+Pilot	-	-	-	-	-	-	-	5X	-	19
	B2b/ 1207.14 (BDS-2)	I	-	-	C7	-	7I	7I	7I	7I	14	5
		Q	-	-	C7	-	7Q	7Q	7Q	7Q	15	6
		I+Q	-	-	C7	-	7X	7X	7X	7X	16	7
	B2b/ 1207.04 (BDS-3)	Data	-	-	-	-	-	-	-	7D	-	-
		Pilot	-	-	-	-	-	-	-	7P	-	-
		Data+Pilot	-	-	-	-	-	-	-	7Z	-	-
	B2a+b/ 1191.795	Data	-	-	-	-	-	-	-	8D	-	-
		Pilot	-	-	-	-	-	-	-	8P	-	-
		Data+Pilot	-	-	-	-	-	-	-	8X	-	-
	B3/ 1268.52	I	-	-	C6	-	6I	6I	6I	6I	8	9
		Q	-	-	C6	-	6Q	6Q	6Q	6Q	9	10
		I+Q	-	-	C6	-	6X	6X	6X	6X	10	11
		B3A	-	-	-	-	-	-	-	6A	-	-

GNSS Signal ID (4/4)

System	Carrier Frequency (MHz)	Channel or Code	RINEX *								RTCM3 MSM[9]	BINEX[10]
			2.10[1]	2.11[2]	2.12[3]	3.00[4]	3.01[5]	3.02[6]	3.03[7]	3.04[8]		
QZSS	L1/ 1575.42	C/A	-	-	-	-	-	1C	1C	1C	2	1
		L1C(D)	-	-	-	-	-	1S	1S	1S	30	2
		L1C(P)	-	-	-	-	-	1L	1L	1L	31	3
		L1C(D+P)	-	-	-	-	-	1X	1X	1X	32	4
		L1-SAIF/L1S	-	-	-	-	-	1Z	1Z	1Z	6	30
	L2/ 1227.60	L2C(M)	-	-	-	-	-	2S	2S	2S	15	8
		L2C(L)	-	-	-	-	-	2L	2L	2L	16	9
		L2C(M+L)	-	-	-	-	-	2X	2X	2X	17	10
	L5/ 1176.45	I	-	-	-	-	-	5I	5I	5I	22	14
		Q	-	-	-	-	-	5Q	5Q	5Q	23	15
		I+Q	-	-	-	-	-	5X	5X	5X	24	16
		L5D (L5S)	-	-	-	-	-	-	-	5D	-	-
		L5P (L5S)	-	-	-	-	-	-	-	5P	-	-
		L5(D+P) (L5S)	-	-	-	-	-	-	-	5Z	-	-
	L6/ 1278.75	L6D	-	-	-	-	-	6S	6S	6S	9	20
		L6P	-	-	-	-	-	6L	6L	6L	10	21
		L6(D+P)	-	-	-	-	-	6X	6X	6X	11	22
		L6E	-	-	-	-	-	-	-	6E	-	-
		L6(D+E)	-	-	-	-	-	-	-	6Z	-	-
SBAS	L1/ 1575.42	C/A	C1	C1	C1	1C	1C	1C	1C	1C	2	1
	L5/ 1176.45	I	-	C5	C5	5I	5I	5I	5I	5I	22	7
		Q	-	C5	C5	5Q	5Q	5Q	5Q	5Q	23	8
		I+Q	-	C5	C5	5X	5X	5X	5X	5X	24	9

* observation code of pseudorange (RINEX 2), band/frequency + attribute (RINEX 3)

[1] RINEX: The receiver independent exchange format version 2.10, Dec 2007, [2]RINEX: The receiver independent exchange format version 2.11, June 2007, [3] RINEX: The receiver independent exchange format version 2.12, June 2009, [4] RINEX - The receiver independent exchange format version 3.00, Nov 2007, [5] RINEX - The receiver independent exchange format version 3.01, June 2009, [6] RINEX - The receiver independent exchange format version 3.02, April 2013, [7] RINEX - The receiver independent exchange format version 3.03, July 2015, [8] RINEX - The receiver independent exchange format version 3.04, Nov 2018 , [9] RTCM standard 10403.3, Differential GNSS (global navigation satellite system) services - version 3, Oct 2016, [10] BINEX: Binary exchange format - BINEX record 0x7f-05: GNSS observable prototyping (https://www.binex.unavco.org/binex.html)