Annex A: Data Formats

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GNSS formats have developed within government, industry, and academia. Their standardization has facilitated the efficient development of the GNSS industry. Current GNSS formats support metadata such as GNSS station, receiver, antenna and equipment calibration information, GNSS observation and broadcast navigation information and also GNSS products such as precise orbits, clock corrections, atmospheric measurements and station coordinates. RINEX, BINEX and IGS standards have been widely accepted and have become de facto standards. RTCM de jure standards on the other hand have developed within a standards organization and were adopted by industry. The development of new GNSS constellations has lead to the need for new formats and also encouraged a higher level of cooperation and integration between the GNSS standards groups. The most widely used GNSS standards are described in this chapter.

The GNSS community relies on a variety of standards that have been developed by different entities to facilitate an interoperable and efficient exchange of data and products between providers and users.

Even though most manufacturers employ company specific – and sometimes nondisclosed – message formats for communication with their GNSS receivers, a variety of nonvendor-specific formats have been developed by various nonprofit organizations [A.1]:

- RTCM SC-104 standard for Differential GNSS Services of the Radio Technical Commission for Maritime Services (RTCM)
- The GNSS-related parts of the NMEA 0183 interface standard of the National Marine Electronics Association (NMEA)
- The Receiver INdependent EXchange (RINEX) format developed by the International GNSS Service (IGS and RTCM SC-104)
- The BINary Exchange (BINEX) format of the University NAVSTAR consortium (UNAVCO).

A subset of these protocols and formats is typically supported in addition (or alternative) to proprietary data formats by all receivers. However, the various standards coexist with each other and the specific standard(s) supported by a given receiver depends largely on the type of user and application.

Complementary to the aforementioned standards for the exchange of GNSS receiver data, a variety of standards have been developed by the IGS to harmonize the exchange of products and metadata. Examples include:

- The Standard Product 3 (SP3) for orbit and clock information,
- The Clock RINEX format for the exchange of postprocessed satellite and receiver clock offset solutions,
- The IONosphere EXchange format (IONEX),
- The ANTenna Exchange (ANTEX) format for the provision of antenna phase center offsets and variations,
- The SiteLog format for station related information, and
- The Solution INdependent EXchange (SINEX) format for a harmonized exchange of estimated parameter sets.

In view of their primary application within the IGS community, the latter standards are generally more open and flexible than formal standards established by industrial or governmental standardization organizations.

Within the following sections the key features of the various standards are briefly described along with illustrating examples. For a more detailed discussion and concise definitions the readers are referred to the official documentation published by the corresponding organization.

A.1 Receiver Formats

A.1.1 NMEA 0183

The National Marine Electronics Association (NMEA) [A.2] is a nonprofit organization that was founded in 1957 by a group of electronic dealers with the goal of strengthening their relationships with electronic manufacturers. NMEA standards include the NMEA 0183 standard (using an ASCII text format) and a modernized version NMEA 2000 (binary). Both standards enable interoperability between marine electronics and support communications as well as data message standards.

The legacy standard (NMEA 0183 [A.3]), which has widely been adopted in GNSS receivers for marine, aeronautical and personal navigation, provides generic specifications of electrical requirements, protocols and message formats for a wide range of devices via a serial interface bus. Such devices may include electronic chart display and information systems, timekeeping equipment, radars, heading sensors, and sounders, LORAN-C (LOng RAnge Navigation) receivers, as well as receivers for global navigation satellite systems.

All NMEA 0183 data are transferred in the form of ASCII text messages via an RS422 (or, alternatively, RS232) serial interface. At a nominal rate of 4800 baud, approximately 600 characters can be transmitted per second, which is generally compatible with the needs of communicating position, speed and auxiliary data of slow moving vessels. Each device sending data is assigned a two letter *talker ID* reflecting the equipment type (Table A.1).

All messages start with a $ sign followed by a five-character string comprising the talker ID (`tt`) and a three character message ID (`mmm`):

```
$ttmmm,d1,d2,...*hh<CR><LF>
```

Following the message header, individual data fields `d1,d2,...` made up of numbers or characters are provided as a comma separated list. The sequence of parameters is specific for each message type. Optional values may be omitted but the separating comma must be provided to enable an unambiguous decoding. The message is terminated by an optional, two-character checksum (introduced by an asterisk) and a set of carriage-return line-feed characters.

An overview of commonly used NMEA 0183 messages for GPS devices is provided in Table A.2. In addition to these, vendor-specific messages are supported by the standard and are in use by various receiver manufactures. These are identified by $P and a three-letter vendor ID instead of the standard message header (e.g., $PUBX and $PASH for uBlox and Ashtech receivers), but otherwise follow the message concept described above.

As an example, the contents of the most widely employed GPS position message ($GPGGA) is illustrated in Fig. A.1. It provides the measured position in terms of geographic longitude and latitude along with the height above sea level but also the difference between ellipsoidal and geoid height assumed used in its computation. Since only the time-of-day is given in the $GPGGA message, a complementary $GPZDA date and time message may need to be output for a unique specification of the current epoch.

Even though common users are mostly interested in position-, velocity- and time-related information, the NMEA 0183 standard also supports a variety of lower-level observation data. This includes a list of visible satellites with information on their line-of-sight direction and received signal strength ($GPGSV) or the range residuals of all satellites used in the navigation solution ($GPGRS). While originally conceived for GPS receivers, the current NMEA 0183 standard also considers other GNSS constellations (GLONASS, Galileo) through dedicated message types and satellite/signal identifiers.

While substantial documentation on the format of the most popular NMEA 0183 GPS messages is available from public Internet sources, users should consider the official standard [A.3] as their primary source of information. It can be obtained directly from the NMEA web site [A.2] at a fee contributed to cover the work of this organization.

Table A.1 Short list of selected NMEA 0183 talker identifications

ID	Device
EC	Electronic chart display & information system
GP	Global Positioning System receiver
IN	Integrated navigation system
RA	Radar
WI	Weather instrument
ZQ	Timekeeper (quartz)

Table A.2 Common NMEA 0183 GNSS messages

Msg ID	Description
$GPALM	GPS almanac data
$GPBOD	Bearing: origin to destination (UTC time, current position, true & magnetic bearing and distance to destination)
$GPDTM	Datum reference
$GPGGA	Global Positioning System fix data (UTC time, position, quality indicators, use of differential corrections)
$GPGLL	Geographic position latitude/longitude
$GPGRS	GPS range residuals
$GPGSA	GPS DOP and active satellites (positioning mode, fix type, satellites used in fix, PDOP, HDOP and VDOP)
$GPGST	GPS pseudorange noise statistics
$GPGSV	GPS satellites in view (number satellites in view, satellite number, azimuth and elevation, signal-to-noise ratio)
$GPHDT	True heading
$GPRMC	Recommended minimum navigation information (UTC time and date, latitude and longitude, speed over ground, status, etc.)
$GPVTG	Course over ground and ground speed
$GPZDA	Time and date (UTC time, calendar date, local time zone UTC offset)

13
1 2 3 4 5 6 7 8 9 10 11 12 14 15

```
$GPGGA,061419,4808.9315,N,01133.9530,E,1,08,1.2,543.2,M,46.9,M,,*4C
```

1	UTC time	($06^h14^m19.0^s$)
2 3	Geographic latitude and hemisphere	(48°08.9315′ North)
4 5	Geographic longitude and hemisphere	(11°33.9530′ East)
6	Quality indicator	(1 = valid GPS navigation fix)
7	Number of satellites in view	(8)
8	Horizontal dilution of precision	(1.2)
9 10	Altitude above mean sea-level (geoid) and unit	(543.2 m)
11 12	Height of geoid above WGS-84 ellipsoid and unit	(46.9 m)
13	Age of differential corrections	(not used)
14	Differential reference station ID	(not used)
15	Checksum	(4C)

Fig. A.1 Example of an NMEA 0813 Global Positioning System Fix Data message ($GPGGA)

A.1.2 RINEX

The Receiver INdependent EXchange (RINEX) format [A.4, 5] was developed under the leadership of *Werner Gurtner*, Astronomical Institute of Bern (AIUB), in 1989. A first version was defined to support the first large European GPS campaign (EUREF 89), where data from four different receiver types was converted from proprietary formats into RINEX 1. In 1990, RINEX 2 supporting both GPS and GLONASS was developed and released. In subsequent years RINEX 2 was continuously updated to support the needs of the GNSS community. The latest release RINEX 2.11 [A.6] supports GNSS observation data for GPS, GLONASS, Galileo, and SBAS, navigation data for GPS, GLONASS, and SBAS as well as a dedicated format for meteorological data.

Even though RINEX 2.11 is still widely used today within the GNSS community, its inherent limitations have long been recognized and led to the development of a new and fully generic multi-GNSS observation and navigation data format. RINEX 3.x was triggered by the gradual buildup of the Galileo system and the ongoing GPS modernization and offers more flexible and detailed observation signal codes than its predecessor. At the same time RINEX 3.x observation records were modified to enable a more human-readable structure. In RINEX 3 complete observation records (pseudorange, phase, signal-to-noise ratio and loss of lock indicator) are provided for each tracked signal. Originally worked out by W. Gurtner (AIUB) and Lou Estey (UNAVCO), the RINEX 3 standard is now jointly maintained by the IGS RINEX Working Group and the RTCM Special Committee 104 (Sect. A.1.3). RINEX Version 3.03 [A.7] released in 2015 supports observation and navigation data for the GPS, GLONASS, Galileo, BeiDou, QZSS, IRNSS/NavIC, and SBAS constellations.

To support both human and machine reading, all RINEX data files employ printable ASCII text formats with predefined field widths for data and labels. A maximum line width of 80 characters is defined for RINEX 2 but has been given up for RINEX 3.x observation files to better accommodate the large number of individual observations available with new and modernized navigation systems.

The complete documentation of the RINEX standard including past and current versions is available from the data server of the IGS web site [A.8].

Observation Data. RINEX 3 observation data files are made up of a variable-length header followed by a series observation record providing the measurements at each epoch. The header is itself made up of a series of individual records with a data section in columns 1–60 and descriptive labels in columns 61–80. It closes with a parameterless `END OF HEADER` line after which the first observation record is given.

As illustrated in Fig. A.2, the header starts with two lines identifying the file type (Observation Data) and format version (3.03) as well as details of its generation. Intermediate header records (shown in red) provide relevant metadata of the station such as a four-letter marker name and a site number, the employed equipment (receiver, firmware, antenna, radome), the approximate coordinates of a surveyed monument marker point, and, finally, the offset of the antenna reference point relative to that marker.

The header continues with a series of `SYS / # / OBS TYPES` records serving as in-

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
     3.03           OBSERVATION DATA    M                   RINEX VERSION / TYPE
sbf2rin-8.5.1       ESA/ESOC            20131107 000707 LCL PGM / RUN BY / DATE
kour                                                        MARKER NAME
97301M210                                                   MARKER NUMBER
Automatic           ESA/ESOC                                OBSERVER / AGENCY
3001301             SEPT POLARX4        2.5.2               REC # / TYPE / VERS
5129                SEPCHOKE_MC     NONE                    ANT # / TYPE
  3839591.4332 -5059567.5514   579956.9164                  APPROX POSITION XYZ
        0.0950        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G   18 C1C L1C D1C S1C C1W S1W C2W L2W D2W S2W C2L L2L D2L  SYS / # / OBS TYPES
       S2L C5Q L5Q D5Q S5Q                                  SYS / # / OBS TYPES
E   16 C1C L1C D1C S1C C5Q L5Q D5Q S5Q C7Q L7Q D7Q S7Q C8Q  SYS / # / OBS TYPES
       L8Q D8Q S8Q                                          SYS / # / OBS TYPES
R   12 C1C L1C D1C S1C C2P L2P D2P S2P C2C L2C D2C S2C      SYS / # / OBS TYPES
C    8 C2I L2I D2I S2I C7I L7I D7I S7I                      SYS / # / OBS TYPES
------------------------------------------------------------------Omitted lines
    30.000                                                  INTERVAL
  2013    11     6     0     0    0.0000000     GPS         TIME OF FIRST OBS
  2013    11     6    23    59   30.0000000     GPS         TIME OF LAST OBS
------------------------------------------------------------------Omitted lines
                                                            END OF HEADER
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
```

Start of header

Site meta data

Observation types

Epoch range

End of header

Fig. A.2 Sample RINEX 3 observation file header from the IGS KOUR station in Kourou, French Guyana. Rulers in the first and last line have been added for illustration only and are not part of the actual file. Colors indicate different groups of header records. Selected records from the original RINEX file have been omitted for brevity

Table A.3 RINEX 3 satellite system identifiers

ID	System
G	GPS
R	GLONASS
S	SBAS payload
E	Galileo
C	BeiDou
J	QZSS
I	IRNSS/NavIC

dex of the observation types provided later for the satellites of each GNSS constellation. The individual constellations are identified by a single-character identifier in column 1 of these records. Currently supported systems and designations are summarized in Table A.3. Except for GPS (G) and SBAS (S) the satellite system identifiers are derived from the nation (Russia, Europe, China, Japan, India) operating the specific constellation.

The individual observations types for each constellation are described by a three-character observation code. Its first character identifies one of the four types of measurements defined in Table A.4. Even though additional pseudo-observations such as channel number (X) and ionospheric phase delay (I) are formally permitted by the RINEX 3 standard, they are rarely used by the community.

Table A.4 RINEX 3 observation types and units

ID	Observation	Units
C	Pseudorange	m
L	Carrier-phase	cy
D	Doppler	Hz
S	Signal strength (C/N_0)	dB-Hz

The second and third characters of the observation code indicate the frequency band (single-digit band number) and the specific modulation or tracking mode (single-letter attribute). Since many of the new and modernized signals comprise multiple components (e.g., an in-phase channel with navigation information and a dataless pilot code on the quadrature channel), distinct attributes are defined for the individual components (e.g., I, Q) and the combined tracking of both components (e.g., X). An overview of currently defined RINEX 3 observation codes is provided in Table A.5.

The observation codes listed in the `SYS / # / OBS TYPES` header records define the set of observations provided for satellites of a given constellation. In the Galileo example of Fig. A.2, a full set of four measurements (pseudorange, carrier-phase, Doppler, signal strength) is specified for tracking of the pilot components of the E1 Open Service (*1C), E5a (*5Q), E5b (*7Q) and E5 AltBOC (*8Q) signals.

Table A.5 RINEX 3 observation codes for carrier-phase observations. Corresponding observation codes with initial letters C, D, and S apply for pseudorange, Doppler and signal strength observations

System	Band	Code	Description
GPS	L1	L1C	C/A-code
		L1S, L1L, L1X	L1C (data, pilot, combined)
		L1P	P-code (unencrypted)
		L1W	Semicodeless P(Y) tracking
		L1Y	Y-code (with decryption)
		L1M	M-code
		L1N	codeless
	L2	L2C	C/A-code
		L2D	Semi-codeless P(Y) tracking (L1 C/A+(P2-P1))
		L2S, L2L, L2X	L2C-code (medium, long, combined)
		L2P	P-code (unencrypted)
		L2W	Semicodeless P(Y) tracking
		L2Y	Y-code (with decryption)
		L2M	M-code
		L2N	codeless
	L5	L5I, L5Q, L5X	L5 (data, pilot, combined)
GLONASS	L1	L1C	C/A-code
		L1P	P-code
	L2	L2C	C/A-code
		L2P	P-code
	L3	L3I, L3Q, L3X	L3 (data, pilot, combined)
SBAS	L1	L1C	C/A-code
	L5	L5I, L5Q, L5X	L5 (data, pilot, combined)
Galileo	E1	L1A	PRS signal
		L1B, L1C, L1X	OS (data, pilot,combined)
		L1Z	PRS + OS(data+pilot)
	E5a	L5I, L5Q, L5X	E5a (data, pilot, combined)
	E5b	L7I, L7Q, L7X	E5b (data, pilot, combined)
	E5	L8I, L8Q, L8X	E5 AltBOC (data, pilot, combined)
BeiDou (BDS-2)	B1	L2I, L2Q, L2X	B1I(OS), B1Q, combined
	B2	L7I, L7Q, L7X	B2I(OS), B2Q, combined
	B3	L6I, L6Q, L6X	B3I, B3Q, combined

Table A.5 (continued)

System	Band	Code	Description
QZSS	L1	L1C	C/A-code
		L1S, L1L, L1X	L1C (data, pilot, combined)
		L1Z	L1-SAIF signal
	L2	L2S, L2L, L2X	L2C-code (medium, long, combined)
	L5	L5I, L5Q, L5X	L5 (data, pilot, combined)
	E6	L6S, L6L, L6X	LEX signal (short, long, combined)
IRNSS/NavIC	L5	L5A	SPS Signal
		L5B, L5C, L5X	RS (data, pilot, combined)
	S	L9A	SPS signal
		L9B, L9C, L9X	RS (data, pilot, combined)

Later, in the observation section of the file, a total of 16 matching measurements will be provided for each Galileo satellite.

A (truncated) example of an observation record corresponding to the header of Fig. A.2 is shown in Fig. A.3. The record starts with an epoch line (marked by a ">" character in column 1) specifying the date and time of the observations (here: 6 Nov 2013 00:00:00.0 GPS time) and the number of tracked satellites (here: 20). Subsequently the observations are provided in a single line for each satellite. The individual satellites are identified in columns 1–3 by the satellite number. This is made up of the satellite system indicator and a two-digit number identifying the transmitted pseudorandom noise (PRN) code or, in case of GLONASS, the slot number of the tracked satellite. Each observation is stored in a fixed field of 14 characters and with three trailing digits after the decimal point. Carrier-phase and pseudorange observations are furthermore complemented by an optional loss-of-lock indicator (0, blank, or 1) and/or a single-digit signal-strength indicator in the two cells adjacent to the actual measurement value.

Although the RINEX format supports the loss-of-lock indicator for each observation type, it is common practice to only indicate it on the phase observations. Likewise, the single-digit signal-strength field is often omitted if the signal strength (in dB-Hz) is explicitly provided as an observation type.

Hatanaka Compression. A practical problem associated with the transfer and storage of RINEX observation data is the large file size caused by the use of

Epoch   No. of satellites   Truncated

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|0---+---9|0---+--10|0---+--11|0---+--12|0---+--13|0---+
> 2013 11 06 00 00  0.0000000  0 20
G21  21789794.010 7 114506100.36007      1720.652 7        47.500    21789793.282 5        35.000    21789800.645 5  89225577.90205 ...
G15  23437270.527 7 123163643.91607      -899.995 7        44.500    23437270.523 5        30.500    23437282.587 5  95971703.90805 ...
G25  23279919.760 6 122336912.64006      2828.062 6        38.250    23279919.300 4        25.750    23279924.875 4  95327536.00104 ...
G05  23600086.200 7 124019495.78607     -1485.409 7        43.500    23600086.267 4        29.750    23600089.098 4  96638667.31304 ...
R20  23006036.629 6 123023649.96106     -1272.486 6        36.000    23006052.039 6  95685099.64406      -989.603 6        38.500    ...
G24  21004445.599 8 110379323.36308     -1995.581 8        50.000    21004445.701 7        43.000    21004451.511 7  86009975.30607 ...
G18  23632299.040 7 124188483.90207      2852.612 7        43.750    23632298.312 4        25.750    23632307.451 4  96770225.02804 ...
G14  25391662.793 5 133434050.21305       442.853 5        35.000    25391662.346 2        12.000    25391683.036 2 103974640.59202 ...
R16  19300482.290 8 103099905.21108       145.853 8        48.250    19300491.076 7  80188907.52507       113.435 7        47.750    ...
G12  21917255.393 8 115176179.65808      1821.021 8        50.000    21917255.309 6        38.250    21917253.796 6  89747789.38406 ...
G29  23768181.065 6 124902773.05306      -802.817 6        41.500    23768180.905 3        22.000    23768182.589 3  97326913.63203 ...
R09  21623927.772 7 115470629.18307      3608.897 7        46.750    21623935.553 6  89810480.72806      2806.903 6        41.000    ...
R06  24236049.702 7 129328208.84807      2479.388 7        44.250
C14  24458718.261 7 127362937.75107      2345.948 7        44.250    24458727.629 8  98485138.61708      1814.036 8        48.000
R15  21481799.314 7 114792351.97907     -3609.734 7        45.000    21481813.243 7  89282811.39807     -2807.690 7        43.250    ...
R04  22254258.875 7 119170642.67807       174.797 7        44.750    22254267.166 6  92688257.97106       135.988 6        38.750    ...
R19  23228568.363 7 124257247.38907     -2230.894 7        42.250    23228573.599 6  96644606.11206     -1735.120 6        36.250    ...
R05  21839218.040 7 116743131.47507      2026.164 7        46.750    21839233.552 7  90800281.60607      1575.910 7        44.000    ...
C12  25394611.396 6 132236540.71606      -985.074 6        40.500    25394615.635 7 102253547.41407      -761.759 7        43.750
C11  25458822.666 7 132570867.23307      -836.718 7        43.250    25458828.466 7 102512178.67707      -647.018 7        43.500
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|0---+---9|0---+--10|0---+--11|0---+--12|0---+--13|0---+
```

Satellite number   Signal strength and loss-of-lock indicators

Fig. A.3 Sample observation record from a RINEX observation file obtained by the IGS KOUR station in Kourou, French Guyana. Rulers in the first and last line have been added for illustration only and are not part of the actual file an ASCII text format. Considering a 30 s sampling, a multi-GNSS reference station with 40 or more commonly tracked satellites provides daily RINEX 3 observations of about 25 MB and an even higher data volume is obtained with 1 Hz high-rate data. This problem can partly be alleviated through standard compression tools such as compress, zip, and rar, which achieve a compression ratio of 1 : 3 to 1 : 4 for typical RINEX files.

A complementary compression technique [A.9], which retains the ASCII representation but reduces the high level of redundancy in the observation data themselves has been developed by *Yuki Hatanaka* at the Geospatial Information Authority (GSI), Japan. It is based on the observation that a time series of consecutive measurements may better be represented by an initial value and the differences between epochs, since the differences are smaller in size than the absolute values and require a reduced number of digits.

Hatanaka compression retains most of the RINEX file header but replaces the observation records with the differenced data and uses a "&" separator between data fields to minimize the overall amount of white space. The resulting *Compact RINEX* format already achieves a file size reduction by a factor of 3–4. In combination with standard file compression tools, an overall reduction by a factor of approximately eight is achieved compared to the original RINEX file. It should be noted that the Hatanaka compression is lossless and enables a full recovery of the original observations data upon decompression.

Navigation Data. As a complement to the observation data format discussed above, the RINEX standard also defines a navigation data format for the exchange of broadcast ephemeris information. These broadcast ephemerides comprise the orbit and clock parameters as well as auxiliary data transmitted by each GNSS satellite for use in real-time navigation. Even though the broadcast ephemerides are generally less accurate than postprocessed ephemeris products, the navigation data files are frequently used for preprocessing of GNSS data (e.g., elevation screening), relative positioning, and as a priori information for precise GNSS orbit and clock determination.

While distinct GPS and GLONASS files were foreseen in early versions, the current RINEX 3 standard supports mixed files with navigation data for all GNSSs. Similar to the observation data format, navigation files are fixed-format text files but are limited to 80 characters per line. The file header follows the same concepts as introduced before and starts with two lines identifying the file type and format version. For the purpose of illustration an annotated format example is given in Fig. A.4.

All header parameters are optional and may comprise different types of ionospheric model parameters and time conversion parameters. These include the eight coefficients $\alpha_0, \dots, \alpha_3$ and $\beta_0, \dots, \beta_3$ of the Klobuchar model for GPS and QZSS users or the Klobuchar-style model employed by BeiDou. For Galileo, a set of four parameters $A_0, \dots, A_3$ is provided that enables ionospheric corrections of single-frequency observations with the NeQuick model. An overview of these models is provided in Chap. 6 and references therein, while detailed information on the application of the broadcast ionospheric parameters is given in the interface specifications of the individual GNSSs [A.10–14].

The remaining header parameters provide the relation of different GNSS timescales among each other and with UTC. These include the number of UTC leapseconds since 1980 (or, equivalently the integer seconds time difference between GPS time and UTC) as well as linear polynomials for the fractional time differences (which typically amount to some tens or at most hundreds of nanoseconds). The individual time correction parameters are identified by a 2 + 2 character code in columns 1–4 of the `TIME SYSTEM CORR` header lines and contain the polynomial coefficients (A_{f0}, A_{f1}) as well as the corresponding reference epoch (week and seconds of week). While not a mandatory header line, provision of the leapseconds information is strongly recommended since it facilitates the translation between the native time systems of each constellation and enables the processing of the subsequent ephemeris data in a consistent timescale.

Following the header, a series of ephemeris data sets for individual satellites and epochs are given. Following the satellite identification and reference epoch, the various ephemeris parameters are provided in fixed fields of 19 characters. The set of parameters and their total is predefined for each individual constellation (GPS, GLONASS, BeiDou, Galileo, QZSS, IRNSS/NavIC, and SBAS) and reflects the different types of information made available in the various types of navigation messages.

Common to all constellations, the satellite clock offset is specified through a clock reference epoch (t_{oc}) and a clock offset polynomial (a_{f0}, a_{f1}, and, for most systems, a_{f2}). For many GNSSs, the clock offset information is complemented by differential code biases (known as timing group delay (TGD), broadcast group delay (BGD) or intersignal correction (ISC) parameters). These enable a consistent processing of the transmitted clock offsets when using single-frequency observations or a different set of signals than the ones used by the control segment to determine the broadcast clock offsets. Clock-related parameters in the format example of Fig. A.4 are highlighted in blue color.

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
    3.03           NAVIGATION DATA     M (Mixed)           RINEX VERSION / TYPE
BCEmerge           MGEX                20131107 044603 GMT PGM / RUN BY / DATE
GPSA   0.2515e-07 -0.7451e-08 -0.1192e-06  0.1192e-06       IONOSPHERIC CORR
GPSB   0.1331e+06 -0.4915e+05 -0.1311e+06 -0.1311e+06       IONOSPHERIC CORR
GAL    1.2525e+02 -5.7031e-01  1.0834e-02  0.0000e+00       IONOSPHERIC CORR
QZSA   0.5122e-07 -0.3353e-06 -0.1192e-06  0.3517e-05       IONOSPHERIC CORR
QZSB   0.1536e+06 -0.8356e+06  0.4063e+07 -0.6554e+07       IONOSPHERIC CORR
GAUT  1.3969838619e-08-5.329070518e-15 172800 1765        0 TIME SYSTEM CORR
GLGP -3.8184225559e-07 0.000000000e+00 259200 1765        0 TIME SYSTEM CORR
GLUT -1.8579885364e-07 0.000000000e+00 259200 1765        0 TIME SYSTEM CORR
GPGA  9.6333678812e-09 5.329070518e-15 345600 1757        0 TIME SYSTEM CORR
GPUT -1.8626451492e-08-0.532907052e-14 405504 1765        0 TIME SYSTEM CORR
QZUT  2.7939677238e-08-3.552713680e-14 491520 1765        0 TIME SYSTEM CORR
    16    16  1694     7                                    LEAP SECONDS
                                                            END OF HEADER
------------------------------------------------------------------------Omitted lines
E12 2013 11 06 02 20 00 3.416970139369e-05 1.233502189280e-11-1.734723475977e-18
     6.200000000000e+01-1.281250000000e+00 3.154417108420e-09-1.584524137928e+00
    -2.607703208923e-08 9.329034946859e-05 1.055561006069e-05 5.440608764648e+03
     2.676000000000e+05 5.774199962616e-08 1.159805493823e+00 5.587935447693e-09
     9.589155555733e-01 1.139062500000e+02-2.779965207269e+00-5.471656487884e-09
     7.568172387615e-10 5.130000000000e+02 1.765000000000e+03
    -1.000000000000e+00 3.900000000000e+02-2.793967723846e-09-2.561137080193e-09
     2.682550000000e+05
------------------------------------------------------------------------Omitted lines
R03 2013 11 06 02 15 00 2.223066985607e-06 0.000000000000e+00 2.664000000000e+05
    -1.547962890625e+03-2.572350502014e+00-3.725290298462e-09 0.000000000000e+00
     1.293956201172e+04 1.558908462524e+00-0.000000000000e+00 5.000000000000e+00
    -2.189239355469e+04 1.099916458130e+00 9.313225746155e-10 0.000000000000e+00
------------------------------------------------------------------------Omitted lines
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
```

Start of header

Ionosphere parameters

Time system parameters

End of header

Galileo ephemeris

GLONASS ephemeris

Field 1	2	3	4	5	Row
Sat	Epoch (t_{oc}, GPS time)	a_{f0} (s)	a_{f1} (s/s)	a_{f2} (s/s^2)	0
	IOD_{nav}	C_{rs} (m)	Δn (rad/s)	M_0 (rad)	1
	C_{uc} (rad)	e	C_{us} (rad)	$\sqrt{a}$ (m$^{1/2}$)	2
	t_{oe} (s)	C_{ic} (rad)	Ω_0 (rad)	C_{is} (rad)	3
	i_0 (rad)	C_{rs} (m)	ω (rad)	$d\Omega/dt$ (rad/s)	4
	di/dt (rad/s)	Data source	Week		5
	Accuracy (m)	Health	BGD_{E5aE1} (sec)	BGD_{E5bE1} (sec)	6
	Transmission time (s)				7

Field 1	2	3	4	5	Row
Sat	Epoch (t_{oc}, UTC)	$a_{f0} = -\tau_N$ (s)	$a_{f1} = +\Gamma_N$ (s/s)	Message frame time (s)	0
	x (km)	dx/dt (km/s)	d^2x/dt^2 (km/s^2)	Health	1
	y (km)	dy/dt (km/s)	d^2y/dt^2 (km/s^2)	Frequency channel k	2
	z (km)	dz/dt (km/s)	d^2z/dt^2 (km/s^2)	Age of information	3

Fig. A.4 Format example of a multi-GNSS RINEX navigation file (*top*). Layout of Galileo and GLONASS ephemeris records (*bottom*; clock and orbit parameters are highlighted by *blue* and *red color*)

Orbit information parameters provided in the individual broadcast navigation data vary among the different constellations, but fall in either of two basic categories: orbital elements ($\sqrt{a}$, e, i_0, Ω_0, ω_0, M_0) and perturbation coefficients (di/dt, $d\Omega/dt$, C_{rc}, C_{rs}, C_{ic}, C_{ic}, C_{uc}, C_{us}) for use with a perturbed Keplerian orbit

0xD3	Res.	n	Message [0, …, n-1]		CRC-24
			Msg.No.	Other data	

Fig. A.5 RTCM SC-104 v3.x message protocol. The first field contains the 8 bit preamble (hex value 0xD3)

model or Cartesian state vectors ($x, y, z, \dot{x}, \dot{y}, \dot{z}, \ddot{x}, \ddot{y}, \ddot{z}$) for numerical integration or polynomial interpolation of the trajectory across short time intervals. Details of the orbit models and the employed parameters are provided in Chap. 3 as well as the interface specifications of the individual constellations [A.10–15]. Broadcast ephemerides with orbital elements are presently used for GPS, QZSS, Galileo, BeiDou, and IRNSS/NavIC while state vectors are provided by the GLONASS and SBAS satellites. The corresponding parameters are highlighted using red color in the format example of Fig. A.4.

Up to version 3.03 the RINEX navigation format supports only legacy navigation data (i. e., one parameter set per constellation), but will be extended for CNAV, CNAV2 and other modernized broadcast ephemeris data sets in subsequent releases.

A.1.3 RTCM SC-104 DGNSS Data Format

The Radio Technical Commission for Maritime Services (RTCM) was formed as a United States government advisory committee in 1947. Currently, the RTCM is an international nonprofit scientific, professional and educational organization that is supported by its members from all over the world. Membership consists of both corporate and government organizations. RTCM members charter Special Committees (SC) to address in-depth radio communication and radio navigation issues, with the goal of supporting interoperability.

RTCM Special Committee 104 (RTCM-SC104) was chartered to address differential global navigation satellite systems (DGNSSs). Initially, RTCM SC-104 focused on standards and protocols for differential GPS for maritime applications. SC-104's mandate has grown to support not only maritime differential GNSS, but also real-time kinematic and precise GNSS data formats and Network Transport of RTCM using Internet Protocol (NTRIP, [A.16]).

The following paragraphs provide an overview of the RTCM SC-104 standard for DGNSS services based on the latest version 3.3 [A.17]. A full specification is available from the RTCM [A.18] at a service fee, which contributes to covering the work of this organization.

Message Types and Format. RTCM SC-104 messages are primarily designed for real-time GNSS applications and use a binary protocol to minimize the overall data volume that needs to be transferred between providers and users. While early versions made use of a message format made up of fixed-length data words with parity protection similar to that of the GPS navigation message, a revised, variable-length message format was introduced for use from version 3.0 onwards. It comprises a header with an 8 bit preamble, 6 bit reserved fields and a 10 bit message length field (Fig. A.5).

Following the header, a data field of up to 1023 bit is provided and the message concludes with a 24 bit cyclic redundancy check (CRC) checksum to ensure integrity of the transmitted data. Except for zero-length filler messages, all messages start with a 12 bit message number that identifies the message type and provides the key to decoding the subsequent message data fields.

RTCM SC-104 v3.x defines various groups of messages for observation data, network RTK corrections, auxiliary and metadata as well as state space correction data (Table A.6). Various multisignal messages provide similar parameters albeit in different combinations and/or resolutions. In this way positioning services of different accuracy may be implemented that make best use of the available communication bandwidth.

Multisignal Messages. Early versions of the RTCM SC-104 standard were strongly focused on the GPS and GLONASS systems and their legacy L1/L2 signals. As of version 3.2, the concept of multisignal messages (MSMs, [A.19]) has been introduced, to establish a truly generic framework for observations of all GNSS constellations and all transmitted signals.

The multisignal messages employ a highly efficient packing scheme, which minimizes the overall amount of data that need to be transmitted. For each observed satellite, the pseudorange and carrier-phase observations are decomposed into the sum of a *rough range* and a *fine range*. The rough range at each epoch is common to all observations of the given satellite collected simultaneously on the individual signals. The remaining fine range reflects the differences in ionospheric path delays and systematic GNSS satellite and receiver biases. It is generally confined to less than ±300 m, which requires considerably fewer data bits for storage than the original value.

Other MSM features include the signal and satellite masks, which serve as an index for the overall set of tracked signals (across all satellites of a constellation) and the subset tracked for a specific satellite. In this way, the presence of modernized signals available for only part of a constellation (e.g., L2C on GPS Block

Table A.6 RTCM SC-104 v3 message groups

Groups	Type	Messages
Experimental messages		0–100
Observations	GPS L1, L1/L2	1001–1004
	GLONASS L1, L1/L2	1009–1012
	Multi Signal Messages for individual GNSSs	1071–1077 (GPS) 1081–1087 (GLONASS) 1091–1097 (Galileo) 1101–1107 (SBAS) 1111–1117 (QZSS) 1121–1127 (BeiDou)
Site metadata	Station coordinates, receiver and antenna description	1005–1008, 1032–1033
Network RTK corrections	Auxiliary station data	1014
	Geometric and ionospheric corrections	1015–1017, 1037–1039
	Network RTK residuals and FKP gradients	1030–1031, 1034–1035
Auxiliary information	System parameters	1013
	Satellite ephemeris	1019, 1020, 1042, 1044, 1045, 1046
	Text (unicode)	1029
	GLONASS code/phase biases	1230
Transformation parameters		1021–1027
State Space Representation parameters	Orbit & clock corrections, code biases, URA	1057–1062 (GPS) 1063–1068 (GLONASS)
Proprietary messages		4001–4095

IIR-M and L5 on Block IIF) can be supported without requiring empty or padded data fields for older satellites.

Finally, a total of seven different multisignal messages are defined for each constellation. The individual message types are distinguished by the final digit of the message number and offer different sets of elementary observations (pseudorange, carrier-phase, signal strength, and Doppler) at different levels (compact, full) of range and resolution.

Network-RTK Messages. Network-RTK refers to real-time kinematic positioning (RTK) using correction data derived from a network of terrestrial reference stations (Chaps. 26 and 31). Compared to a single reference station, the network-based corrections can be applied in a wider region and the quality of carrier-phase ambiguity resolution becomes less dependent on the base station distance. The RTCM SC-104 standard offers a harmonized framework for transmitting such corrections to the user independent of the underlying network architecture. Both GPS and GLONASS network-RTK services are supported through dedicated messages. Aside from station-related information provided in the auxiliary station data message, *geometric* (nondispersive) and *ionospheric* (dispersive) correction data may be transmitted in distinct or combined messages. Details of the respective messages and the applicable processing conventions are provided in the RTCM SC-104 standard [A.17]. Another class of network-RTK messages comprises the *Network-RTK Residual Error* messages, which are used to implement concepts such as virtual base stations to improve the RTK service for specific users.

State-Space Representation Messages. The state-space representation (SSR) represents a new concept for the provision of correction data in real-time kinematic precise point positioning (PPP-RTK) applications. Rather than providing combined corrections in observation space, the SSR approach employs decomposed corrections to remove individual GNSS error sources [A.20]. These include satellite position corrections (in three dimensions) and satellite clock corrections as well as code biases. Different message types are supported for individual or combined orbit and clock corrections. Furthermore, distinct high-rate clock correction messages are available to ensure that satellites with fast changing atomic clocks can be accurately characterized. The SSR concept also foresees the provision of vertical total electron content (VTEC) information for single-frequency users, even though these are not yet part of the RTCM SC-104 standard. The generic nature of the SSR corrections makes them largely independent from the user location and provides the basis for global PPP applications.

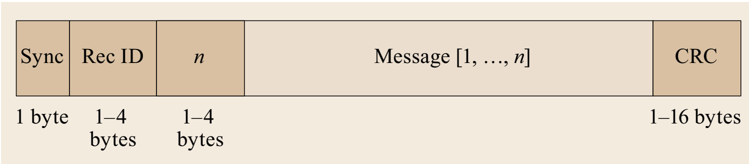

Fig. A.6 Basic BINEX message protocol

A.1.4 GNSS BINary Exchange (BINEX) Format

The BINary Exchange (BINEX) format, is a GNSS format standard that supports both research and operational applications. BINEX was developed at UNAVCO under the leadership of *Lou Estey* (UNAVCO) to achieve a better data compression and increased reliability for real-time data streams from permanent GPS monitoring stations [A.21, 22]. Other than common binary formats, BINEX is designed to support both little-endian and big-endian word-orders, which allows use on a wide range of hardware platforms and processors. Also, a wide range of message lengths is supported through checksum and message number fields with a varying number of bytes. The BINEX format supports observation and navigation messages for all current GNSS constellations as well as meta-data messages to encapsulate site-specific parameters. BINEX is supported by major GNSS receiver manufacturers (Trimble, Topcon, Javad, Leica, Septentrio) and is continuously extended and refined to meet the needs of new signals and systems. The official documentation of the BINEX format is maintained as a living document on the UNAVCO web site [A.23].

Record Structure. BINEX data files are made up of a sequence of consecutive BINEX data records that can be processed independent of each other. Since BINEX files do not contain a file header, multiple BINEX files can easily be concatenated for further processing without the need for special tools. The BINEX standard supports various generic forms of message frames for different applications. These are designed to enable any foreseeable type of GNSS receiver data, auxiliary information as well as final data products.

In their most simple (and widely used) form, each record comprises a header with synchronization byte, record identifier and message length field before the actual message data and concludes with a checksum field (Fig. A.6). The message itself may contain additional fields (subrecord ID, etc.) to further distinguish the actual contents.

Both the record identifier and the message length are stored in an *unsigned BINEX integer* (ubnxi) data word, which occupies between 1–4 byte depending on the size of the encoded value. Likewise, different types of checksum (1 byte XOR checksum, 2 byte CRC-16, or 4 byte CRC-32) are employed depending on the length of the message data field.

Table A.7 Common BINEX record types

ID	Sub ID	Contents
0x00		Site Metadata
0x01		GNSS Navigation Information
	0x00	• coded (raw bytes) GNSS ephemeris
	0x01	• decoded GPS ephemeris
	0x02	• decoded GLONASS-FDMA ephemeris
	0x03	• decoded SBAS ephemeris
	0x04	• decoded Galileo ephemeris
	0x05	• decoded Beidou-2/Compass ephemeris
	0x06	• decoded QZSS ephemeris
	0x07	• decoded IRNSS ephemeris
	0x41–0x47	• raw navigation subframe/block/page for individual constellations
0x7d		Receiver Internal State
	0x00	• Temperature and power
0x7e		Ancilliary Site Data Prototyping
	0x00	• Meteorological and local geophysical data
0x7f		GNSS Observable Prototyping
	0x00	• for JPL LEO support network
	0x01	• for UCAR COSMIC and GPS/MET
	0x02	• for UCAR Suominet
	0x03	• for EarthScope
	0x04	• for EarthScope
	0x05	• Generic multi-GNSS observation data

Message Types. While BINEX is a highly generic protocol intended to support the binary transfer of all types of GNSS-related information, only a limited number of messages are widely used at present. All of these employ a 1 byte record identifier and belong to one of five major categories shown in Table A.7.

For most record types, the message fields start with a 1 byte subrecord ID to further distinguish the data contained within. Even though records 0x7e and 0x7f are formally considered as prototype messages that shall eventually be replaced by 0x03 and 0x02 messages, some of them (such as 0x7f 0x05) represent a de facto standard and have already been adopted by various receiver manufacturers.

In addition to the public messages described in Table A.7, various record identifiers have been assigned to different institutions or companies to enable the implementation of private BINEX messages. These make use of record IDs beyond 0x7f (= 127) that require more than one byte for ubnxi encoding.

A.2 IGS Product and Metadata Formats

Complementary to the text and binary formats for exchange of receiver-related information (observations, navigation data, metadata, etc.) a wide range of different formats have been developed in the frame of the International GNSS Service (IGS). These enable a consistent exchange of GNSS data products and auxiliary information among users and analysis centers. Most common examples include precise orbit and clock information, atmospheric products, antenna information and site metadata, all of which are described in this section. Current and past versions of the various format specifications are available in electronic form through the IGS web site [A.8].

A.2.1 SP3 Ephemeris Format

The *Standard Product 3 (SP3)* format defines a widely used standard for the provision of precise orbit and clock data of GNSS satellites. Aside from RINEX observation data, the SP3 orbit and clock information forms the basis of most precise point positioning (PPP) applications. IGS orbit and clock products are consistently made available in SP3 format by the various analysis centers and can be utilized by all common PPP software packages.

SP3 originates from two types of GPS orbit data formats (SP1, SP2) developed by the US National Geodetic Survey (NGS). Other than its predecessors that were limited to orbit-only data, SP3 also incorporates clock data and accuracy information [A.24]. Even though both text and binary versions have originally been defined, only the former has found widespread acceptance and continues to be developed. In its latest version, SP3d, the format supports all GNSS constellations using satellite identifiers consistent with those of the RINEX standard (Sect. A.1.2). To facilitate a joint use for precise orbit information of satellites in low Earth orbit (LEO), a constellation letter "L" has furthermore been introduced for non-GNSS satellites in addition to the designations in Table A.3.

Even though the SP3 format is specifically designed to combine orbit and clock offset information in a fully consistent manner, clock data are often desired at higher rate. In view of their smooth motion, GNSS orbits with periods of 12–24 h can readily be interpolated from known values at a 15 min spacing or more. Clock variations, on the other hand, are governed by stochastic processes and a smaller sampling interval (down to 30 s or less) is required for accurate interpolation. PPP users may therefore prefer to complement SP3 orbit data with separate high-rate clock data (Sect. A.2.2), provided that both products have been generated by a common provider, using fully consistent processes.

Format Description. The basic format and contents of an SP3d orbit and clock data file are illustrated in Fig. A.7 based on the comprehensive specification in [A.25]. It comprises a header section with auxiliary information for the proper processing of the subsequent data records. These provide orbit and clock data as well as optional accuracy and event information on an equidistant epoch grid for a previously specified number of satellites and epochs. While the format was originally limited to a line width of 80 characters and a 22-line header, a larger number of header lines has been introduced in SP3d to accommodate more than 85 satellites and extended comments.

The file header comprises various blocks of lines (introduced by `#`, `+`, `%`, and `/` characters), which provide relevant indices and parameters for the proper interpretation of the subsequent orbit, clock and accuracy data records.

The first header line indicates the format version ("`d`" for SP3d in column 2) and distinguishes position-only files from files with position and velocity information ("`P`" or "`V`" in column 3). Thereafter the calendar date of the initial epoch and the number of data points is provided. Along with the stepsize provided in columns 25–38 of line 2, the epochs of all subsequent orbit and clock data records are fully defined by this header information. Complementary to the specification of the start epoch in line 1, a (redundant) representation in terms of weeks and seconds as well as integer and fractional Modified Julian Day count are given in line 2. Further information in the first header includes an indicator for the employed data (e.g., `u+U` for undifferenced carrier-phase and code observations), the coordinate system descriptor, the type of orbit product and an acronym of the responsible institution.

Following these initial header lines, a block of five or more lines introduced by a single + character specifies the total number of satellites, the satellite identifiers (constellation letter plus number) and the sequence of satellites for which orbit and clock data are later given in the epochwise SP3 data blocks. The next header block (highlighted in red in Fig. A.7) provides integer-valued orbit accuracy indicators a for each spacecraft, from which the standard deviation $\sigma_{\mathrm{orb}} = 2^a$ mm of the respective orbit errors across all epochs can be obtained.

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
#dP2014  1 14  0  0  0.00000000      96   u+U IGb08 FIT  GFZ
## 1775 172800.00000000   900.00000000 56671 0.0000000000000
+   55   G01G02G03G04G05G06G07G08G09G10G11G12G13G14G15G16G17
+        G18G19G20G21G22G23G24G25G26G27G28G29G31G32R01R02R03
+        R04R05R06R07R08R09R10R11R12R13R14R15R16R17R18R19R20
+        R21R22R23R24 00 00 00 00 00 00 00 00 00 00 00 00 00
+         00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
++         6  6  7  7  6  6  7  6  6  5  7  5  8  5  8  9  6
++         6  6  7  7  5  6  9  6  5  5  6  8  5  6  7  6  5
++         8  8  5  8  5  8  6  8  6  9 10  8  5  7  6  6 10
++         8  5  5  6  0  0  0  0  0  0  0  0  0  0  0  0  0
++         0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
%c  M 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
%i    0    0    0    0      0      0      0      0         0
%i    0    0    0    0      0      0      0      0         0
/* PCV:IGS08_1771 OL/AL:FES2004  NONE     YN CLK:CoN ORB:CoN
/*     Format example
/*
/*
*  2014  1 14  0  0  0.00000000
PG01 -22719.489032 -12954.464685   4947.520826    100.299587 18 18 16 217
PG02   9976.466832  20308.487654  14556.052309    472.605048 18 17 17 205
PG03  -6463.720164 -14712.776290 -21679.213455    312.055000 21 19 20 235
PG04  -5817.639961  14805.054074  20935.719513      4.845698 20 18 19 227     M
PG05   3611.450463  24622.788248  -9096.600235   -392.445998 17 19 18 210
---------------------------------------------------------------------------- Omitted lines
...
PR20 -22545.743726  -3235.075024 -11530.456734    -87.973609 30 27 29 276
PR21 -24750.255662   4458.159423   3954.708793 999999.999999 25 23 26 999 EP   P
PR22 -14589.418582  10212.984872  18328.006528    110.608442 16 16 16 193
PR23   5123.982462  10175.849396  22816.989886   -588.600287 16 17 16 187
PR24  20756.252131   4380.870362  14144.802842   -105.908108 17 18 19 207
---------------------------------------------------------------------------- Omitted lines
...
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
```

Start of header

Satellite list

Global accuracy codes

Parameters

Comments

Epoch
Sat, orbit, clock,
accuracy codes,
flags

Fig. A.7 SP3d format example

The header continues with a block of auxiliary parameters, most notably the time system indicator in the first line starting with `%c`. It concludes with a block of four or more comment lines used within the IGS to identify various processing conventions such as antenna offset or tide models.

Each of the subsequent data blocks starts with an epoch header line specifying the epoch date and time, which must be consistent with the sequence of the record and the epoch grid defined in the file header. Thereafter, the position (in units of km) and clock offset (in μs) are specified for each satellite in lines marked by an initial "`P`" character. For files containing both position and velocity information, each position record is complemented by a subsequent velocity record (indicated by the initial "`V`" character), which provides the spacecraft velocity (in units of 0.1 m/s) and clock rate (in 10^{-4} μs). Unknown or invalid data in both records are indicated by zero values (position and velocity) or 999999.999999 (clock offset and clock rate).

Fig. A.7 also illustrates the use of optional epoch- and componentwise accuracy indicators (columns 62–73) as well as additional flags (columns 75–80 for clock events ("`E`"), orbit maneuvers ("`M`") and predicted orbit or clock data ("`P`"). Similar to the global accuracy indicators described above, these indicators provide the exponent a for computing the standard deviation of the respective value using a relation of the form $\sigma = b^a$. Other than using a fixed base of $b = 2$, the base value can be selected by the provider and is separately specified in the `%f` header line for position and clock data. In this way a better resolution of the accuracy information is achieved. Using epochwise accuracy indicators is optional but enables a better distinction of predicted orbit and clock information from values based on actual observations.

For completeness, we note that the SP3 standard also foresees the use of an optional position and clock correlation record (EP) as well as a corresponding EV record for velocity and clock rate information. These records enable provision of a fully four-dimensional covariance matrix to describe the statistical properties of the respective data. However, neither the position nor the clock correlation records have found widespread acceptance in official IGS products.

Interpolation. Based on its history, SP3 is designed as a tabular ephemeris format, which provides all data at equal intervals. This is a natural choice for orbit information generated by numerical orbit prediction software and facilitates the interpolation of intermediate values. Having said that, some synchronization may be required to ensure that clock data can be made available at the same epochs as the orbit information. Even though the SP3 format supports the joint provision of epochwise position and velocity data, it has been recognized that position-only information is generally sufficient, since velocity can be obtained from these data through differentiation of an interpolating function. Versions with and without complementary velocity (and clock rate) data are therefore supported by the SP3 format. Aside from their reduced size, position-only SP3 files ensure full consistency of the derived position-velocity information and avoid the cumbersome transformation of inertial to Earth-fixed velocity data.

Various forms of interpolators for GNSS ephemeris data have been proposed and studied in the literature [A.26–28], but polynomial interpolation is probably most widely used. A variety of algorithms have been developed for this purpose [A.29], among which the Lagrange method appears best suited when multiple values (such as the x-, y-, and z-coordinates of the position vector) have to be interpolated on the same epoch grid. It is therefore commonly recommended for use with SP3 orbit data [A.24, 30, 31].

Given a set of $n+1$ epochs t_i, the elementary nth-order Lagrange polynomials

$$l_i(t) = \prod_{j=0, j\neq i}^{n} \frac{(t-t_j)}{(t_i-t_j)} \qquad (i = 0, \ldots, n) \tag{A.1}$$

are first computed. These are designed to vanish at all but one grid point, i. e.,

$$l_i(t_j) = \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \quad \text{for} \quad \begin{Bmatrix} i = j \\ i \neq j \end{Bmatrix} . \tag{A.2}$$

With this result the interpolating polynomial of order n can conveniently be expressed as a linear combination

$$\boldsymbol{r}(t) = \sum_{i=0}^{n} \boldsymbol{r}_i l_i(t) , \tag{A.3}$$

where $\boldsymbol{r}_i$ denotes the values of the position vectors at the given grid points. The velocity at time t can likewise be obtained through Lagrange interpolation

$$\boldsymbol{v}(t) = \sum_{i=0}^{n} \boldsymbol{v}_i l_i(t) , \tag{A.4}$$

based on known values $\boldsymbol{v}_i$ at the grid epochs. Alternatively, the interpolating polynomial (A.3) may be differenced to obtain the relation

$$\boldsymbol{v}(t) = \sum_{i=0}^{n} \boldsymbol{r}_i l'_i(t) , \tag{A.5}$$

where

$$l'_i(t) = \sum_{\substack{k=0 \\ k\neq i}}^{n} \frac{1}{(t-t_k)} \cdot \prod_{\substack{j=0 \\ j\neq i}}^{n} \frac{(t-t_j)}{(t_i-t_j)} \tag{A.6}$$

denotes the time derivative of the nth-order Lagrange polynomial. It may be noted that the above expressions are also applicable for interpolation of nonequidistant values. However, a constant step size (as implied by the SP3 format) simplifies the computation of the Lagrange polynomials and contributes to an even distribution of interpolation errors.

At the 15 min spacing adopted for most GNSS orbit products, a ninth-order polynomial using an equal number of grid points on both sides of the interpolation epoch offers an interpolation accuracy compatible with the numerical resolution of the SP3 orbit data [A.26]. However, larger interpolation errors may be encountered near the beginning or end of the ephemeris period [A.27]. Also, high-order interpolation must not be applied to clock data, which are not as smooth as the orbit information. Here, linear interpolation or at most cubic interpolation [A.32] is recommended.

Conventions. To enable a consistent use of multi-GNSS orbit and clock files, the SP3 standard requires that information for all satellites shall refer to a common time and reference system identified in the file header. Despite this, further specifications by the product provider will typically be required for the proper interpretation of the data.

Within the IGS, GNSS satellite positions provided in the SP3 precise ephemeris products are referred to the spacecraft center-of-mass and a mean-crust-fixed terrestrial coordinate system (which may differ by a few millimeters from a barycentric system due to tidal deformation of the Earth).

Clock data, in contrast, refer to an adopted antenna phase center and a conventional dual-frequency signal combination (L1/L2 P(Y)-code observations for GPS).

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
     3.00           CLOCK DATA          G                   RINEX VERSION / TYPE
goaLib.tdp2rnxClk   JPL                 20140123 180643 UTC PGM / RUN BY / DATE
G    4 C1P L1P C2P L2P                                      SYS / # / OBS TYPES
   GPS                                                      TIME SYSTEM ID
G GIPSY/PvsCA       CODE's 30-day GPS P1-C1 DCB solution    SYS / DCBS APPLIED
G GIPSY             IGS08_1740                              SYS / PCVS APPLIED
     2    AR    AS                                          # / TYPES OF DATA
JPL  JPL USING GIPSY/OASIS-II                               ANALYSIS CENTER
     1                                                      # OF CLK REF
USN3 40451S007                                              ANALYSIS CLK REF
    80    IGb08                                             # OF SOLN STA / TRF
AB11 UNKNOWN                 -2658010411  -693674824  5737338498SOLN STA NAME / NUM
ANKR 20805M002                4121948460  2652187872  4069023826SOLN STA NAME / NUM
AREQ 42202M005                1942826240 -5804070343 -1796894183SOLN STA NAME / NUM
...                                                                Omitted lines
YAKT 12353M002               -1914999151  2308241477  5610225509SOLN STA NAME / NUM
YARR 50107M006               -2389025300  5043315501 -3078533281SOLN STA NAME / NUM
ZAMB 34601M001                5415352973  2917210074 -1685888704SOLN STA NAME / NUM
    31                                                      # OF SOLN SATS
G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 PRN LIST
G16 G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G31 PRN LIST
G32                                                         PRN LIST
                                                            END OF HEADER
AR AB11 2014  1 15  0  0  0.000000  2    6.499754781087e-08  8.439171608513e-11
AR ANKR 2014  1 15  0  0  0.000000  2    9.769804722732e-05  8.756057498951e-11
...                                                                Omitted lines
AR YARR 2014  1 15  0  0  0.000000  2    3.572224937511e-09  8.625967501824e-11
AR ZAMB 2014  1 15  0  0  0.000000  2   -7.047014800876e-08  8.572597246593e-11
AS G01  2014  1 15  0  0  0.000000  2    1.005156164617e-04  7.551891115286e-11
AS G02  2014  1 15  0  0  0.000000  2    4.727939503967e-04  7.355088299119e-11
...                                                                Omitted lines
AS G31  2014  1 15  0  0  0.000000  2    3.323450819402e-04  7.201648815328e-11
AS G32  2014  1 15  0  0  0.000000  2   -5.016907537156e-04  7.131600355336e-11
...                                                                Omitted lines
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
```

Start of header

Processing parameters

Station list

Satellite list

End of header

Station (receiver) clock offsets

Satellite clock offsets

Fig. A.8 RINEX clock format example

Furthermore, the dominant relativistic contribution to the apparent clock caused by the orbital eccentricity has been removed from the provided clock data to better reflect the clock's proper time. As such, a corresponding correction must be added to clock offsets retrieved from the SP3 ephemeris for the proper modeling of GNSS observations (Sect. 19.2).

A.2.2 Clock RINEX Format

The *RINEX Extensions to Handle Clock Information* [A.33] were introduced in 1998 as a generic framework for the exchange of general clock offset information. Today, the format is primarily used to provide precise GNSS satellite and receiver clock data derived from the analysis of global networks of monitoring stations. Despite its name, the Clock RINEX format has therefore evolved to a GNSS product format rather than a receiver data format. Clock RINEX data are widely used for precision point positioning (PPP) and also to monitor the performance of GNSS satellite clocks and atomic clocks of national time standard laboratories.

The structure and contents of a Clock RINEX file are illustrated in Fig. A.8. In accordance with RINEX observation and navigation data formats (Sect. A.1.2), the clock data file header is made up of a sequence of header lines identified by their labels in columns 61–80. These mandatory or optional header lines provides auxiliary information for the proper interpretation of the actual clock data and are terminated by a `END OF HEADER` line. Key parameters provided within the header comprise a time system indicator, information on the signal or signal combination used in the clock offset determination for each GNSS constellation, information on the application of phase center offsets, phase pattern variations and differential code biases, and the station clock serving as a reference for all clock offsets. Additionally, lists of all stations and satellites used in the clock offset estimation process are provided.

The subsequent data section of the RINEX clock file provides clock offset values for each of these stations and receivers on an epoch-by-epoch basis. The respective lines are marked by a leading "`AR`" (for analysis data, receivers) and "`AS`" (for analysis data, satellites) and contain explicit epoch information. The remaining fields specify the number of data items followed by the clock offset and, optionally, its standard deviation. Both values are provided in units of seconds. If desired, clock rate and acceleration as well as their standard deviation may also be given on a continuation line.

A fixed stepsize is not required but it is a common practice among the IGS analysis centers. Depending on the product and provider, step sizes of 5 min and 30 s are most frequently used, but 5 s products are also available for high-precision applications. Linear interpolation of clock data between consecutive epochs is recommended in view of the stochastic nature of typical clock variations.

A.2.3 SINEX

The Solution INdependent EXchange (SINEX) format [A.34] was originally designed to facilitate the exchange and distribution of station coordinates, velocities and Earth orientation parameters (EOP) between the IGS analysis centers. These parameters are routinely estimated from the processing of the global IGS GNSS network using a wide range of software tools. A common format was therefore required to enable a comparison and combination of the analysis center solutions. SINEX has been used for this purpose from 1995 onwards and received continuous amendments to handle new parameters over the past decades.

The format has also been adopted and extended to meet the needs of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) techniques. The combination of these techniques is used to generate the International Terrestrial Reference Frame (ITRF).

A basic SINEX file contains station coordinate and Earth rotation parameter estimates along with auxiliary information about the site, such as receiver and antenna type, eccentricity and phase center information. In addition, covariance information or normal equations can be stored to facilitate the combination of solutions from different analysis centers and/or geodetic observation systems [A.35].

SINEX employs a fixed-format text representation with a maximum line width of 80 characters. Each file is started with a mandatory `%=SNX` header line and terminated with an `%ENDSNX` footer. In between, various blocks of data may be given in arbitrary order. Each block is identified by a predefiend label and embedded in a frame of *+label* ... *-label* lines. An overview of SINEX data blocks file is given in Table A.8 and a format example is provided in Fig. A.9.

SINEX Troposphere Format. The SINEX troposphere format [A.36] extends the SINEX format to capture tropospheric observations and estimates. The format can contain the total and wet zenith path delays, precipitable water vapor, and gradients thereof along with the respective standard deviations. In addition, standard atmospheric measurements such as barometric pressure, temperature, and relative humidity can be provided. GNSS users can use the SINEX troposphere data to correct the range observations to improve the position estimate. Weather reporting and prediction agencies also use the observed and estimated meteorological data contained in the SINEX troposphere file for numerical modeling and climatological archives.

SINEX troposphere files follow the overall conventions of a standard SINEX file format and inherit various of its data blocks, but are identified by a `%=TRO` header line. A list of labels specific to the troposhere format is provided in Table A.9.

Bias SINEX Format. Following the example of the SINEX troposphere format, a tailored SINEX version has also been proposed for the exchange of code and phase biases of satellites and GNSS monitoring stations [A.37]. The format is specifically designed to handle differential code biases (DCB), but can also handle carrier-phase and intersystem biases. A list of associated labels for the bias-specific data blocks is provided in Table A.9. SINEX bias files are distinguished from standard SINEX files through the `%=BIA` header line.

A.2.4 IONEX Format

The IONosphere EXchange (IONEX) format [A.38] has been developed for the exchange of global ionosphere maps (GIMs) derived from the analysis of GNSS observations. Aside from space weather monitoring and ionospheric analyses, these maps enable more accurate and precise single-frequency position estimates than the Klobuchar or NeQuick models (Chap. 6) used for real-time ionospheric correction inside a GNSS receiver.

GIM products in IONEX format are generated by various IGS analysis centers [A.39] and provide estimated vertical total electron content (VTEC) values on an equidistant grid in geo*centric* longitude and latitude at discrete time intervals (Fig. A.10). These are used in combination with a single-layer model (Chaps. 6 and 19) to compute the ionospheric path delays in the processing of pseudorange and phase observations.

```
%=SNX2.01COD14:019:09616IGS14:013:0000014:016:00000P008481SEA
*-------------------------------------------------------------------------------
+FILE/REFERENCE
 DESCRIPTIO        CODE, Astronomical Institute, University of Bern
 OUTPU             CODE IGS 3-day solution
 INPU              CODE IGS 1-day solutions
-FILE/REFERENCE
*-------------------------------------------------------------------------------
+SITE/ID
*CODE PT __DOMES__ T _STATION DESCRIPTION__ APPROX_LON_ APPROX_LAT_ _APP_H_
 ABMF  A 97103M001 P LesAbymes, FR          298 28 20.9  16 15 44.3   -25.6
 ZIMJ  A 14001M006 P Zimmerwald, CH           7 27 54.4  46 52 37.7   954.3
-SITE/ID
+SITE/RECEIVER
*SITE PT SOLN T DATA_START__ DATA_END____ DESCRIPTION_________ S/N__ FIRMWARE___
 ABMF  A    1 P 14:013:00000 14:015:86370 TRIMBLE NETR9        ----- -----------
 ZIMJ  A    1 P 14:013:00000 14:015:86370 JAVAD TRE_G3TH DELTA ----- -----------
-SITE/RECEIVER
+SITE/ANTENNA
*SITE PT SOLN T DATA_START__ DATA_END____ DESCRIPTION_________ S/N__
 ABMF  A    1 P 14:013:00000 14:015:86370 TRM57971.00     NONE -----
 ZIMJ  A    1 P 14:013:00000 14:015:86370 JAVRINGANT_DM   NONE -----
-SITE/ANTENNA
+SITE/GPS_PHASE_CENTER
*DESCRIPTION_________ S/N__ L1->ARP(M)_(U,E,N)__ L2->ARP(M)_(U,E,N)__
 JAVRINGANT_DM   NONE ----- 0.0893 0.0011 0.0009 0.1196 0.0003 -.0001 IGS08_1771
 TRM57971.00     NONE ----- 0.0668 0.0011 -.0003 0.0578 0.0001 0.0007 IGS08_1771
-SITE/GPS_PHASE_CENTER
+SITE/ECCENTRICITY
*SITE PT SOLN T DATA_START__ DATA_END____ AXE ARP->BENCHMARK(M)_________
 ABMF  A    1 P 14:013:00000 14:015:86370 UNE   0.0000   0.0000   0.0000
 ZIMJ  A    1 P 14:013:00000 14:015:86370 UNE   0.0770   0.0000   0.0000
-SITE/ECCENTRICITY
*-------------------------------------------------------------------------------
+SATELLITE/ID
*SITE PR COSPAR___ T DATA_START__ DATA_END____ ANTENNA_____________
 G063 01 2011-036A P 11:197:00000 00:000:00000 BLOCK IIF
 R735 24 2010-007B P 10:060:00000 00:000:00000 GLONASS-M
-SATELLITE/ID
+SATELLITE/PHASE_CENTER
*SITE L SATA_Z SATA_X SATA_Y L SATA_Z SATA_X SATA_Y MODEL_____ T M
 G063 1 1.5613 0.3940 0.0000 2 1.5613 0.3940 0.0000 IGS08_1771 A E
 R735 1 2.4830 -.5450 0.0000 2 2.4830 -.5450 0.0000 IGS08_1771 A E
-SATELLITE/PHASE_CENTER
*-------------------------------------------------------------------------------
+SOLUTION/EPOCHS
*CODE PT SOLN T _DATA_START_ __DATA_END__ _MEAN_EPOCH_
 ABMF  A    1 P 14:013:00000 14:015:86370 14:014:43185
 ZIMJ  A    1 P 14:013:00000 14:015:86370 14:014:43185
-SOLUTION/EPOCHS
+SOLUTION/ESTIMATE
*INDEX TYPE__ CODE PT SOLN _REF_EPOCH__ UNIT S __ESTIMATED VALUE____ _STD_DEV___
     1 STAX   ABMF  A    1 14:014:43200 m    2 0.291978574407741E+07 .346952E-03
     2 STAY   ABMF  A    1 14:014:43200 m    2 -.538374500399109E+07 .547673E-03
     3 STAZ   ABMF  A    1 14:014:43200 m    2 0.177460477599520E+07 .307686E-03
   769 STAX   ZIMJ  A    1 14:014:43200 m    1 0.433129380015458E+07 .353701E-03
   770 STAY   ZIMJ  A    1 14:014:43200 m    1 0.567542294104827E+06 .204759E-03
   771 STAZ   ZIMJ  A    1 14:014:43200 m    1 0.463313582612440E+07 .365545E-03
   778 XPO    ---- --    1 14:013:00000 mas  2 0.301765028159985E+02 .775857E-02
   782 YPO    ---- --    1 14:013:00000 mas  2 0.329956712999544E+03 .781743E-02
   786 UT     ---- --    1 14:013:00000 ms   2 -.110025006935236E+03 .145173E-03
   793 SATA_Z G063 LC ---- 14:014:43185 m    2 0.156129999660433E+01 .145173E-05
   848 SATA_Z R735 LC ---- 14:014:43185 m    2 0.248300000792411E+01 .145173E-05
-SOLUTION/ESTIMATE
*-------------------------------------------------------------------------------
%ENDSNX
```

Fig. A.9 SINEX format example. Labels as well as header, trailer and comment lines are highlighted in color

Table A.8 Common SINEX data blocks; (m), (r), and (o) indicate mandatory, recommended and optional blocks

Label		Contents
FILE/REFERENCE	(m)	Information on organization, software and hardware used in the file generation
FILE/COMMENT	(o)	General comments on the SINEX file
INPUT/HISTORY	(r)	Information on the agency, source data period, techniques, parameters, and content type (station, orbit, EOP, troposphere, etc.)
INPUT/FILES	(o)	Source data files
INPUT/ACKNOWLEDGEMENTS	(o)	List of contributing agencies
NUTATION/DATA	(m, VLBI)	Employed nutation model (IAU1980, IERS1996, IAU2000a/b)
PRECESSION/DATA	(m, VLBI)	Employed precession model (IAU1976, IER1996)
SOURCE/ID	(m, VLBI)	Designation of VLBI radio sources
SITE/ID	(m)	Description of key site parameters (identifiers, observation techniques, description, approximate location)
SITE/RECEIVER	(m)	Employed receivers (type, serial number, timespan) for each site
SITE/ANTENNA	(m)	Employed antennas and radomes (type, serial number, timespan) for each site
SITE/GPS_PHASE_CENTER	(m)	GPS L1/L2 phase center offsets of each antenna type
SITE/GAL_PHASE_CENTER		Galileo E1/E5a/E6/E5b/E5ab phase center offsets of each antenna type
SITE/ECCENTRICITY	(m)	Eccentricities, i. e., distances of antenna reference point from surveyed marker for each site
SATELLITE/ID	(r)	List of employed GNSS satellites with antenna type (or block), space vehicle and COSPAR number as well as associated RINEX/SP3 satellite identifier (=PRN/slot number) and period of use/assignment
SATELLITE/PHASE_CENTER	(m)	GNSS satellite antenna phase center offsets from the center-of-mass for each frequency band
SOLUTION/EPOCHS	(m)	List of observation timespan for each solution, site and point for which parameters have been estimated
BIAS/EPOCHS	(r/m)	Type (range, time, scale, etc.) and period of biases estimated in individual solutions
SOLUTION/STATISTICS	(o)	Statistical properties (no. of observations and unknowns, sampling, residuals, etc.)
SOLUTION/ESTIMATE	(m)	Estimated values and standard deviations of all solution parameters
SOLUTION/APRIORI	(r/m)	A priori values and constraints applied in the estimation
SOLUTION/MATRIX_ESTIMATE	(r/m)	Upper or lower triangle of correlation, covariance, or information matrix
SOLUTION/MATRIX_APRIORI	(m)	A priori correlation, covariance, or information matrix in triangular form
SOLUTION/NORMAL_EQUATION_VECTOR	(m)	Right-hand side of the unconstrained (reduced) normal equation
SOLUTION/NORMAL_EQUATION_MATRIX	(m)	Unconstrained normal equations matrix in triangular form

Table A.9 Data blocks specific to the SINEX Troposphere and SINEX Bias formats; (m) indicates mandatory blocks

Label		Contents
TROP/DESCRIPTION	(m)	Values of analysis parameters (sampling interval, elevation cutoff, mapping function, etc.) and list of parameters provided in the solution (estimated zenith delays, meteorological data, etc.)
TROP/STA_COORDINATES	(m)	Employed stations and their coordinates
TROP/SOLUTION	(m)	Values of estimated parameters at discrete time steps for each site
BIAS/DESCRIPTION	(m)	Specification of solution parameters (sampling interval, etc.)
BIAS/SOLUTION	(m)	Type of bias (signals, satellite, station), period of applicability, value and standard deviation

Format Description. The IONEX file format follows the RINEX2 template with 80 column records. It contains a file header followed by a TEC map for each epoch. Each TEC map is itself made up of multiple records providing TEC values for a given latitude over the specified longitude grid (Fig. A.11). Optionally,

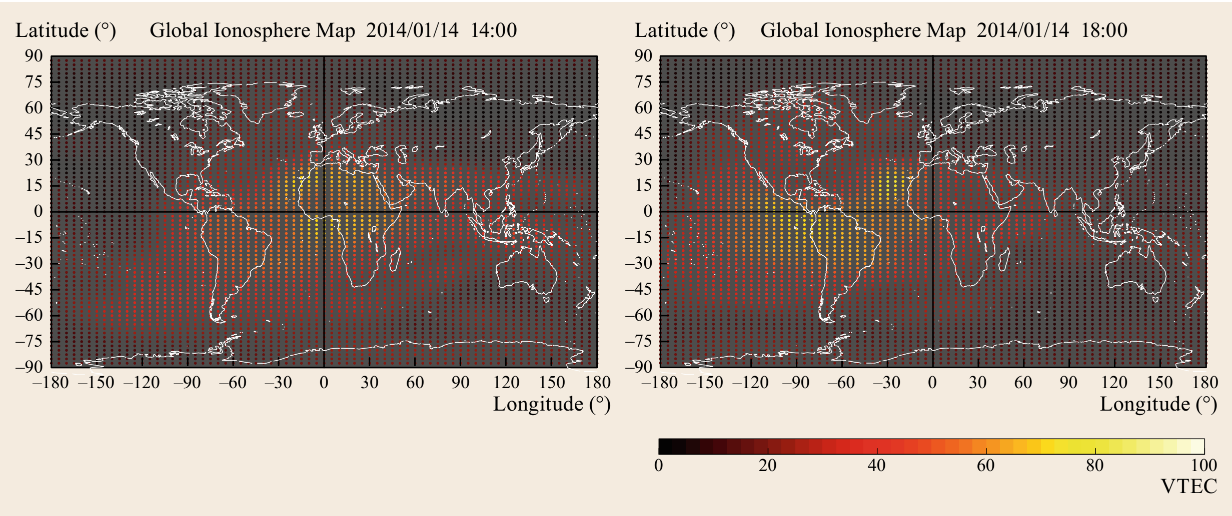

Fig. A.10 Global ionosphere maps of the IGS CODE analysis center

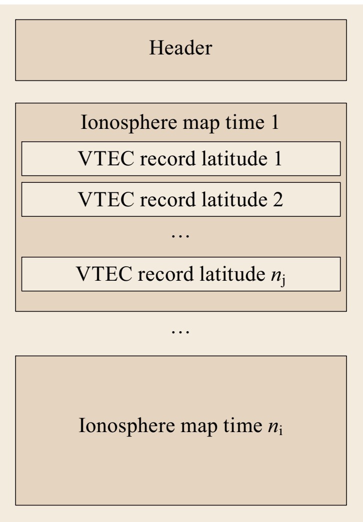

Fig. A.11 IONEX file structure

the TEC maps may be complemented by RMS TEC maps providing the expected uncertainty of the TEC values.

A truncated example illustrating the basic format of the IONEX header and data records is shown in Fig. A.12. The header primarily specifies the range in time, longitude and latitude as well as the corresponding step sizes for the TEC information given in the various TEC maps. Even though the format is designed to support three-dimensional maps, current products are confined to two-dimensional single-layer representation with a fixed height relative to a specified mean Earth radius. To facilitate interpolation, both 00:00 h and 24:00 h epochs are usually included in the daily IONEX products. Likewise, the longitude grid for global maps includes TEC values for $\lambda = -180°$ and $\lambda = +180°$ despite the resulting redundancy. A second set of header lines provides the set of differential code biases (DCBs) of all satellites and stations incorporated in the generation of the TEC maps. Since ionospheric path delays are retrieved from differences of observations made at two different frequencies (Chap. 39) such biases have a direct impact on the estimated ionospheric activity. Provision of the biases in the file header ensures full transparency and consistency, even though the values are not actually required, to use TEC maps in single-frequency positioning applications.

Each TEC map is made up of a series of consecutive records providing the TEC values over the full set of longitude grid points at a specified latitude. Using a predefined scale of typically 0.1 TECU, all values can be represented through integer numbers with at most five digits. Individual TEC maps are embedded in a `START OF TEC MAP` and `END OF TEC MAP` frame and marked by their sequence number. Furthermore, the calender date and time of the respective epoch are provided to ease their identification.

Interpolation. The global ionosphere maps provide the values $\mathrm{VTEC}_{i,j,k}$ of the vertical total electron contents at discrete times t_i, geocentric latitudes φ'_j, and longitudes λ_k (Fig. A.10). Application of the single-layer model requires interpolation of these values for a given time t and location (λ, φ') of the ionospheric pierce point (i. e., the point at which the signal path intersects the thin shell used to represent the ionosphere; see Chap. 19, Fig. 19.1).

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
     1.0            IONOSPHERE MAPS     GNSS                IONEX VERSION / TYPE
ADDNEQ2 V5.3        AIUB                18-JAN-14 21:04     PGM / RUN BY / DATE
CODE'S GLOBAL IONOSPHERE MAPS FOR DAY 014, 2014             COMMENT
Web page:        www.aiub.unibe.ch/content/ionosphere/      DESCRIPTION
  2014     1    14     0     0     0                        EPOCH OF FIRST MAP
  2014     1    15     0     0     0                        EPOCH OF LAST MAP
  7200                                                      INTERVAL
    13                                                      # OF MAPS IN FILE
  NONE                                                      MAPPING FUNCTION
    10.0                                                    ELEVATION CUTOFF
One-way carrier phase leveled to code                       OBSERVABLES USED
   278                                                      # OF STATIONS
    56                                                      # OF SATELLITES
  6371.0                                                    BASE RADIUS
     2                                                      MAP DIMENSION
   450.0 450.0   0.0                                        HGT1 / HGT2 / DHGT
    87.5 -87.5  -2.5                                        LAT1 / LAT2 / DLAT
  -180.0 180.0   5.0                                        LON1 / LON2 / DLON
    -1                                                      EXPONENT
TEC/RMS values in 0.1 TECU; 9999, if no value available     COMMENT
DIFFERENTIAL CODE BIASES                                    START OF AUX DATA
   G01   -10.591     0.007                                  PRN / BIAS / RMS
...---------------------------------------------------------------------------- Omitted lines
   R  ZIMJ 14001M006         -13.992     0.038              STATION / BIAS / RMS
DCB values in ns; zero-mean condition wrt satellite values  COMMENT
DIFFERENTIAL CODE BIASES                                    END OF AUX DATA
                                                            END OF HEADER
     1                                                      START OF TEC MAP
  2014     1    14     0     0     0                        EPOCH OF CURRENT MAP
    87.5-180.0 180.0    5.0 450.0                           LAT/LON1/LON2/DLON/H
   23   23   24   25   26   27   28   29   30   31   32   33   34   34   35   36
   36   37   37   38   38   38   38   38   37   37   37   36   36   36   35   35
   34   34   34   33   33   33   33   33   32   32   32   32   32   32   32   31
   31   31   30   30   29   29   28   28   27   26   26   25   24   24   23   23
   22   22   22   22   22   22   22   22   23
...---------------------------------------------------------------------------- Omitted lines
   -87.5-180.0 180.0    5.0 450.0                           LAT/LON1/LON2/DLON/H
  190  190  191  191  191  191  190  190  189  188  188  187  186  185  184  183
  182  181  179  178  177  176  175  174  173  171  170  169  168  167  165  164
  163  162  161  160  158  157  157  156  155  154  154  154  153  153  154  154
  154  155  156  157  158  159  161  163  164  166  168  170  172  174  176  178
  180  182  183  185  186  187  188  189  190
     1                                                      END OF TEC MAP
...---------------------------------------------------------------------------- Omitted lines
                                                            END OF FILE ...
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
```

Start of header

Specifcation (data grid, etc.)

Code biases

End of header

TEC records

End of file

Fig. A.12 IONEX file format example. Rulers at the start and end have been added for information only and are not part of the actual format

For interpolation to the given location a bilinear interpolation

$$\begin{aligned}\mathrm{VTEC}_i(\lambda,\varphi') = {} & (1-p)(1-q)\mathrm{VTEC}_{i,j,k} \\ & +(p)(1-q)\mathrm{VTEC}_{i,j+1,k} \\ & +(1-p)(q)\mathrm{VTEC}_{i,j,k+1} \\ & +(p)(q)\mathrm{VTEC}_{i,j+1,k+1}\end{aligned} \tag{A.7}$$

with coefficients

$$\begin{aligned}p &= (\varphi'-\varphi'_j)/(\varphi'_{j+1}-\varphi'_j) \\ q &= (\lambda-\lambda_k)/(\lambda_{k+1}-\lambda_k)\end{aligned} \tag{A.8}$$

is applied across the intervals $\varphi'_j \le \varphi' < \varphi'_{j+1}$ and $\lambda_k \le \lambda < \lambda_{k+1}$, limited by the surrounding grid points.

For interpolation in time, a linear interpolation

$$\begin{aligned}\mathrm{VTEC}(t,\lambda,\varphi') = {} & (1-\tau)\mathrm{VTEC}_i(\lambda,\varphi') \\ & +\tau\mathrm{VTEC}_{i+1}(\lambda,\varphi')\end{aligned} \tag{A.9}$$

with $\tau = (t-t_i)/(t_{i+1}-t_i)$ can subsequently be employed across the time interval $t_i \le t < t_{i+1}$. Improved results may, however be obtained, by taking into account that ionospheric activity varies mostly with local time rather than UTC. This results in an apparent westwards shift of the average electron density distribution at a rate of $\omega = 15\,^\circ/\mathrm{h}$, which is illustrated in Fig. A.10. A modified relation

$$\begin{aligned}\mathrm{VTEC}(t,\lambda,\varphi') = {} & (1-\tau)\mathrm{VTEC}_i(\lambda,\varphi') \\ & +\tau\mathrm{VTEC}_{i+1}(\lambda-\omega(t_{i+1}-t_i),\varphi')\end{aligned} \tag{A.10}$$

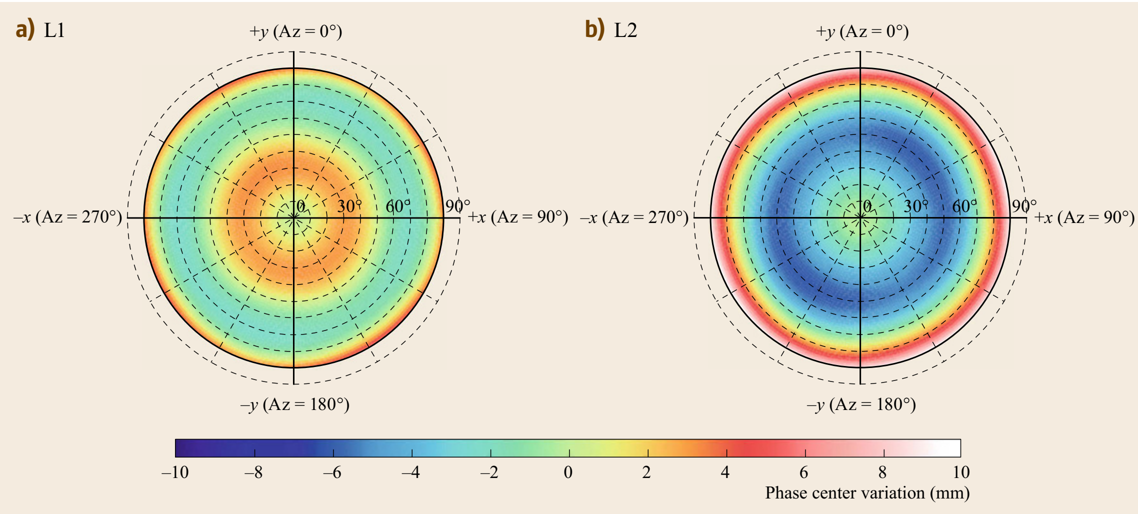

Fig. A.13 Azimuth and boresight angle-dependent phase center variation of Leica AR25.R4 antenna as provided in the igs08.atx antenna calibration file for GPS L1 **(a)** and L2 **(b)** signals. Image courtesy of A. Hauschild

is therefore recommended by [A.38] for interpolation of IONEX TEC maps in time. Here, the second map is shifted in longitude with respect to the first one to compensate for Earth rotation between the respective epochs.

A.2.5 ANTEX

The ANTenna EXchange (ANTEX) format [A.40] was developed to facilitate the documentation and distribution of phase center offsets (PCOs) and phase center variations (PCVs) for GNSS receiver and satellite antennas (Fig. A.13). These corrections are used in GNSS precise point positioning applications as well as GNSS satellite orbit and clock determination for high-accuracy modeling of carrier-phase observations (Chap. 19).

Except for PCV data that require an extended line width, ANTEX files employ a line format with parameters in columns 1–60 and descriptive labels in columns 61–80. Following a brief header, a series of data records with information for individual antennas are provided (Fig. A.14). Each record is itself made up of an antenna-specific header and several sets of PCO/PCV data for distinct constellations and frequency bands.

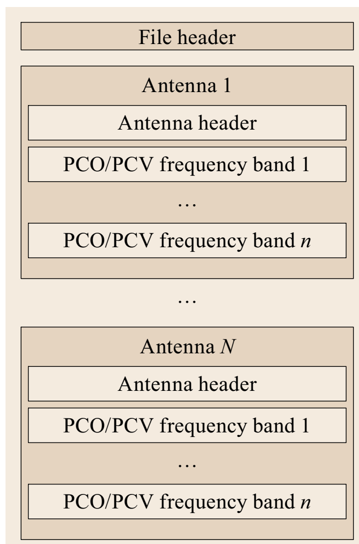

Fig. A.14 Basic structure of ANTEX antenna data files

A truncated format example illustrating the basic structure of the ANTEX file and the data blocks is provided in Fig. A.15. Different colors are used to highlight the header of individual antenna records (blue) as well as PCO/PCV data for the GPS L1 (red) and L2 (green) frequency. For GNSS satellite antennas, the antenna type (associated with the block type of a GPS satellite), the three-character RINEX satellite identifier (constellation letter and PRN or slot number), the space vehicle number and the international (COSPAR) satellite number are specified in the first record header line. Next, the grid of azimuth and boresight angle values for the provision of phase center variations is specified. In addition, a validity period is specified that reflects the timespan during which the space vehicle was assigned the given satellite identifier. For GNSS receiver antennas, the antenna and radome name are identified along with the method used for calibration of the phase pattern. Since 2005, absolute antenna phase patterns are exclusively used within the IGS [A.41]. These may be based on either robot calibrations or anechoic chamber measurements.

```
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
     1.4           M                                        ANTEX VERSION / SYST
A                                                           PCV TYPE / REFANT
                                                            END OF HEADER
                                                            START OF ANTENNA
BLOCK IIF           G25                 G062      2010-022A TYPE / SERIAL NO
                    COD/ESA                  0    25-MAR-11 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  17.0   1.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
  2010     5    28     0     0    0.0000000                 VALID FROM
   G01                                                      START OF FREQUENCY
    394.00      0.00   1597.30                              NORTH / EAST / UP
   NOAZI    6.10    4.40    2.80    1.30   -0.20   -1.40   -2.80   -3.90   ...    18.20   23.50
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
    394.00      0.00   1597.30                              NORTH / EAST / UP
   NOAZI    6.10    4.40    2.80    1.30   -0.20   -1.40   -2.80   -3.90   ...    18.20   23.50
   G02                                                      END OF FREQUENCY
                                                            END OF ANTENNA
                                                            START OF ANTENNA
AOAD/M_T        NONE                                        TYPE / SERIAL NO
ROBOT               Geo++ GmbH                   2    25-MAR-11 METH / BY / # / DATE
     5.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
   G01                                                      START OF FREQUENCY
      0.58     -0.37     91.85                              NORTH / EAST / UP
   NOAZI    0.00   -0.23   -0.90   -1.93   -3.22   -4.62   -5.96   -7.09   ...     9.08   14.23
     0.0    0.00   -0.27   -0.98   -2.07   -3.42   -4.87   -6.26   -7.43   ...     8.68   13.67
     5.0    0.00   -0.27   -0.98   -2.06   -3.41   -4.86   -6.25   -7.41   ...     8.73   13.73
 ----...-----...-----...-----...-----...-----...-----...-----...-----...-----...--...
   355.0    0.00   -0.27   -0.98   -2.07   -3.42   -4.88   -6.27   -7.43   ...     8.65   13.64
   360.0    0.00   -0.27   -0.98   -2.07   -3.42   -4.87   -6.26   -7.43   ...     8.68   13.67
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
     -0.08     -0.59    120.35                              NORTH / EAST / UP
   NOAZI    0.00   -0.13   -0.51   -1.08   -1.79   -2.58   -3.39   -4.17   ...     5.68    9.44
     0.0    0.00   -0.12   -0.48   -1.02   -1.69   -2.44   -3.24   -4.04   ...     5.50    9.31
     5.0    0.00   -0.12   -0.48   -1.02   -1.69   -2.44   -3.24   -4.03   ...     5.45    9.20
 ----...-----...-----...-----...-----...-----...-----...-----...-----...-----...--...
   355.0    0.00   -0.13   -0.49   -1.03   -1.69   -2.44   -3.24   -4.04   ...     5.55    9.43
   360.0    0.00   -0.12   -0.48   -1.02   -1.69   -2.44   -3.24   -4.04   ...     5.50    9.31
   G02                                                      END OF FREQUENCY
                                                            END OF ANTENNA
----+---1|0---+---2|0---+---3|0---+---4|0---+---5|0---+---6|0---+---7|0---+---8|
```

File header

Satellite antenna data

Receiver antenna data

Omitted lines

Omitted lines

Fig. A.15 ANTEX file format example. Rulers at the start and end have been added for information only and are not part of the actual format. Ellipses denote characters or lines that have been deleted to fit the available print space

Antenna information for a specific frequency band is embedded in a `START OF FREQUENCY` …`END OF FREQUENCY` block identified by the RINEX constellation letter and frequency band number. The offset of the antenna phase center is first provided, thereafter the phase center variations are given. Receiver antenna phase center offsets are defined with respect to the antenna reference point (ARP) and a coordinate system aligned with the nominal North, East, and Up directions. GNSS satellite phase center offsets are defined with respect to the satellites center-of-mass and body-fixed x-, y- and z-coordinates. Phase center variations referring to the same reference system are provided in the form of an averaged boresight angle-dependent pattern (marked by the `NOAZI` keyword) as well as an optional azimuth and boresight angle-dependent pattern. For GNSS satellites only the first form is presently provided in the standard IGS ANTEX product, although various efforts have already been made to derive two-dimensional PCV maps for all GPS and GLONASS satellites. For a given boresight direction, the PCV maps can be interpolated using either linear (for one-dimensional PCVs) or bilinear interpolation (for two-dimensional PCVs).

A.2.6 Site Log Format

Building and maintaining a GNSS station or network of stations requires a standardized station information archive that describes the station including location, equipment, responsible agency and contact information. To meet these needs, the IGS has established a dedicated site log format. Site logs are stored as text files with an 80-character width and made up of 14 numbered sections described in Table A.10. Indi-

```
    KZN2 Site Information Form
    International GNSS Service

0.  Form
    Prepared by (full name)    : Renat Zagretdinov
    Date Prepared              : 2012-02-24
    Report Type                : NEW

1.  Site Identification of the GNSS Monument
    Site Name                  : KAZAN
    Four Character ID          : KZN2
    Monument Inscription       : KFU GNSS STATION
    IERS DOMES Number          : 12374M001
    CDP Number                 : NONE
    Monument Description       : PILLAR
      Height of the Monument   : 13(m)
      Monument Foundation      : CONCRETE BLOCK
      Foundation Depth         : 2(m)
    Marker Description         : (CHISELLED CROSS/DIVOT/BRASS NAIL/etc)
    Date Installed             : 2010-10-01
    Geologic Characteristic    : CLAY and SAND
    ...

2.  Site Location Information
    City or Town               : KAZAN
    State or Province          : TATARSTAN
    Country                    : Russian Federation
    Tectonic Plate             : Eurasian
    Approximate Position (ITRF)
      X coordinate (m)         : 2352345.7
      Y coordinate(m)          : 2717466.1
      Z coordinate(m)          : 5251458.5
      Latitude (N is +)        : +554726.82
      Longitude (E is +)       : +0490709.28
      Elevation (m,ellips.)    : 94.6
    Additional Information     :

3. GNSS Receiver Information
3.1 Receiver Type              : TRIMBLE NETR9
    Satellite System           : GPS+GLO+GAL+CMP
    Serial Number              : 5049K72275
    Firmware Version           : 4.43
    Elevation Cutoff Setting   : 5
    Date Installed             : 2012-02-24T00:00Z
    Date Removed               : 2012-08-14T13:00Z
    Temperature Stabiliz.      : 20-30
    ...

4. GNSS Antenna Information
4.1 Antenna Type               : TRM59800.00
    Serial Number              : 5106354023
    Antenna Reference Point    : BPA
    Marker->ARP Up Ecc. (m)    : 0.0750
    Marker->ARP North Ecc (m)  :
    Marker->ARP East Ecc (m)   :
    Alignment from True N      : 0
    Antenna Radome Type        : SCIS
    Radome Serial Number       : 0702
    Antenna Cable Type         : LMR400, Times Microwave Systems
    Antenna Cable Length       : 30(m)
    Date Installed             : 2012-02-24T00:00Z
    Date Removed               : (CCYY-MM-DDThh:mmZ)
...
```

Fig. A.16 Site log format example (truncated sections are indicated by ellipses)

Table A.10 Sitelog file contents

No.	Section	Contents
0	Form	Lists the author, preparation date, type (new or update), link to previous site log and list of changes
1	Site identification	Site name, four-character ID, monument inscription, IERS domes number, CDP number; monument description, height (m) and foundation (type and depth); marker description and date installed, geological characteristics of foundation (soil, rock)
2	Site location	City or town, state, country, tectonic plate, approximate Cartesian and and geographic coordinates
3	GNSS receiver	Receiver type, GNSS systems supported, serial number, firmware version, elevation cutoff angle, date (installed and removed). Repeated for each change
4	GNSS antenna	Antenna type, serial number, antenna reference point (ARP), marker-to-antenna ARP offset, antenna alignment w.r.t true north, radome type and serial number, antenna cable type and length, date (installed and removed). Repeated for each change
5	Surveyed local ties	Tied marker: name, usage (SLR, VLBI, control), CDP number, domes number, differential components (ITRS) (m) : dx, dy and dz, accuracy, survey method, date and additional information as required. Repeated for each additional tie and campaign
6	Frequency standard	Type (internal, external and type), input frequency, effective dates beginning and end. Repeated for each change
7	Collocation information	List of instrumentation present an the site: type (DORIS, SLR, VLBI, etc.), status, effective dates (start and end) and notes
8	Meteorological instrumentation	Humidity sensor: manufacturer, serial number, sampling interval, accuracy, aspiration, height difference to antenna, calibration date and start and end date. Corresponding information for pressure sensor, temperature sensor, water vapor radiometer and other meteorological sensors
9	Local conditions	Radio interference, multipath sources, signal obstruction
10	Local episodic effects	Date, event (tree clearing, construction, etc.)
11	On site contact	Agency, abbreviation, address, primary contact: name, telephone, fax and email, repeated for secondary contact and additional information
12	Responsible agency	Same content as in site contact section
13	More information	Primary and secondary data center, URL for station information, availability of site map, diagram, horizon mask, detailed monument description and pictures, antenna graphics and additional information

vidual parameters within each section are identified by predefined labels with colons in column 31 separating the labels and parameters. When equipment or site conditions change the relevant block is updated. In this way, site logs provide users with a complete record of all the changes that have taken place. A truncated format example of a site log file is shown in Fig. A.16.

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Annex B: GNSS Parameters

Oliver Montenbruck, Michael Meurer, Peter Steigenberger

This chapter summarizes important GNSS-related parameters. Next to general physical constants, key parameters of the GNSS constellations and the various GNSS signals are provided.

B.1 Physical Constants

Physical constants and parameters of relevance for the generation and processing of GNSS observations are provided in Table B.1.

B.2 Orbital Parameters

Table B.2 summarizes the orbital parameters of current global and regional navigation satellite systems.

B.3 Signals

The spectra of current and planned GNSS navigation signals are illustrated in Fig. B.1. Key parameters of the individual signals are compiled in Table B.3.

Signal bandwidths (BW) given in the table refer to the location of the first minimum outside the main lobe(s). The actual spectral usage depends on the filtering and may cover a larger frequency range, particularly when sharing a frequency band with other wideband signals. GNSS signals are commonly described as

$$S = s_{\mathrm{I}} \cos(2\pi f t) \pm s_{\mathrm{Q}} \sin(2\pi f t) \,, \tag{B.1}$$

where the *cos*-component of the signal is designated as the *in-phase* component (I), while the *sin*-signal is termed the *quadrature* component (Q) [B.11]. Depending on the choice of sign in the above equation, the instantaneous phase of the Q-channel is either behind (plus-sign) or ahead (minus-sign) of the I-channel. To distinguish both options, we use the notations

$$S = s_{\mathrm{I}^+} \cos(2\pi f t) + s_{\mathrm{Q}^+} \sin(2\pi f t) \tag{B.2}$$

and

$$S = s_{\mathrm{I}^-} \cos(2\pi f t) - s_{\mathrm{Q}^-} \sin(2\pi f t) \,, \tag{B.3}$$

for the specification of the channel (Ch), where the superscript of the I- and Q-symbols indicates the employed signal description. In the absence of a superscript, the association of signals to the I- and Q-channel and/or the concise phase relation is not traceable from public information. However, signals designated as *I* and *Q*, respectively, are known to be modulated in phase-quadrature with respect to each other.

Table B.1 Physical constants and parameters

Quantity	Description	Value	Unit	References and remarks
Time				
TT–TAI	Time offset TT and TAI	32.184	s	IAU 1991 [B.1]
GPST–TAI	Time offset GPS time and TAI	≈ -19	s	[B.2]
BDT–TAI	Time offset BDS time and TAI	≈ -33	s	[B.3]
Universal				
c	Speed of light in vacuum	$2.99792458 \cdot 10^{8}$	$\mathrm{m\,s^{-1}}$	Defining constant [B.4]
G	Constant of gravitation	$6.67408 \cdot 10^{-11}$	$\mathrm{m^3\,kg^{-1}\,s^{-2}}$	[B.4]
μ_0	Permeability of vacuum	$12.566370614 \ldots \cdot 10^{-7}$	$\mathrm{N\,A^{-2}}$	$4\pi \cdot 10^{-7}$ [B.4]
ϵ_0	Permittivity of vacuum	$8.854187817 \ldots \cdot 10^{-12}$	$\mathrm{F\,m^{-1}}$	$1/\left(\mu_0 c^2\right)$ [B.4]
e	Elementary charge	$1.6021766208 \cdot 10^{-19}$	C	[B.4]
m_e	Electron mass	$9.10938356 \cdot 10^{-31}$	kg	[B.4]
Earth				
$GM_\oplus$	Geocentric grav. constant	$3.986004415 \cdot 10^{14}$	$\mathrm{m^3\,s^{-2}}$	EGM2008, TT-compatible [B.5]
J_2	Dynamic form factor	$1.08263 \cdot 10^{-3}$		GRS80 [B.6]
$R_\oplus$	Equatorial radius	$6.378137 \cdot 10^{6}$	m	GRS80 [B.6]
$1/f$	Flattening factor	298.257222101		GRS80 [B.6]
$\omega_\oplus$	Nominal mean angular velocity	$7.292115 \cdot 10^{-5}$	$\mathrm{rad\,s^{-1}}$	GRS80 [B.6]
Sun				
$GM_\odot$	Heliocentric grav. constant	$1.32712440040944 \cdot 10^{20}$	$\mathrm{m^3\,s^{-2}}$	DE421 [B.7]
AU	Astronomical unit	$1.49597870700 \cdot 10^{11}$	m	[B.8]
$R_\odot$	Mean solar radius	$6.96 \cdot 10^{8}$	m	[B.9]
TSI	Total solar irradiance	1360.8	$\mathrm{W\,m^{-2}}$	[B.10]
$P_\odot$	Radiation pressure at 1 AU	$4.5391 \cdot 10^{-6}$	$\mathrm{N\,m^{-2}}$	TSI/c
Moon				
$GM_☾$	Selenocentric grav. constant	$4.902800076 \cdot 10^{12}$	$\mathrm{m^3\,s^{-2}}$	DE421 [B.7]
$R_☾$	Mean lunar radius	$1.7374 \cdot 10^{6}$	m	[B.9]

Table B.2 Representative orbital parameters (period, semi-major axis a, height above the Earth h, eccentricity e, and inclination i) of global and regional navigation satellite system satellites. A period of n/m revolutions (rev) per sidereal day ($\mathrm{d_{sid}}$) results in a ground-track repeat track after m inertial rotations of the Earth (approximately $m \times 23^{\mathrm{h}}56^{\mathrm{m}}$)

System	Period (rev/$\mathrm{d_{sid}}$)	Period (h)	a (km)	h (km)	e	i (°)
GLONASS	17/8	$11^{\mathrm{h}}16^{\mathrm{m}}$	25 510	19 130	0.0	64.8
GPS	2/1	$11^{\mathrm{h}}58^{\mathrm{m}}$	26 560	20 180	0.0	55
BeiDou (MEO)	13/7	$12^{\mathrm{h}}53^{\mathrm{m}}$	27 910	21 530	0.0	55
Galileo	17/10	$14^{\mathrm{h}}05^{\mathrm{m}}$	29 600	23 220	0.0	56
QZSS (IGSO)	1/1	$23^{\mathrm{h}}56^{\mathrm{m}}$	42 160	35 790	0.1	43
BeiDou (IGSO)	1/1	$23^{\mathrm{h}}56^{\mathrm{m}}$	42 160	35 790	0.0	55
IRNSS (IGSO)	1/1	$23^{\mathrm{h}}56^{\mathrm{m}}$	42 160	35 790	0.0	29
BeiDou/IRNSS/QZSS (GEO), SBAS	1/1	$23^{\mathrm{h}}56^{\mathrm{m}}$	42 160	35 790	0.0	≤ 2

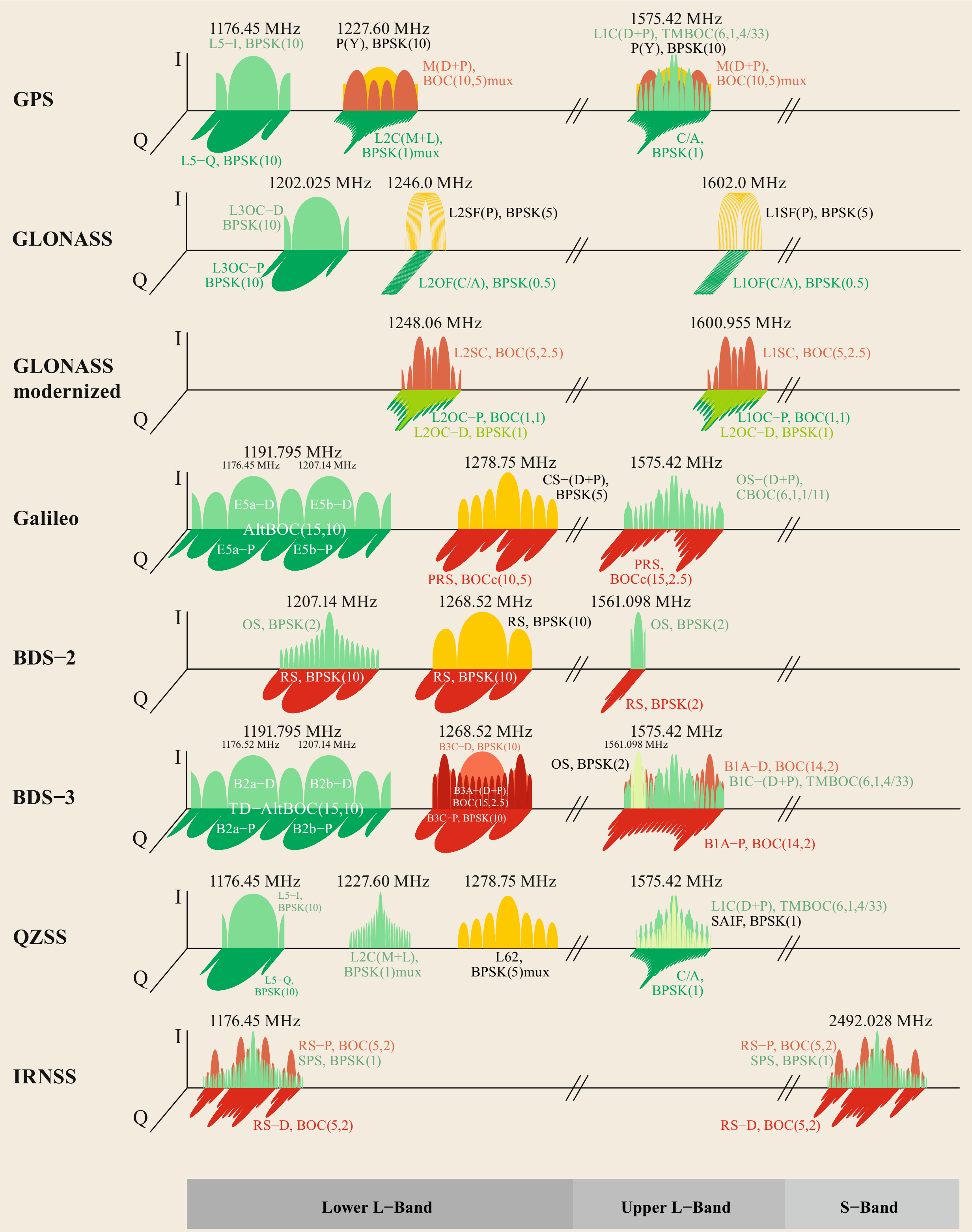

Fig. B.1 GNSS signals overview. Colors indicate open signals (*shades of green*), authorized signals (*shades of red*), and signals that can be tracked with restrictions (*yellow*)

Table B.3 GNSS signals overview. The specified bandwidth (BW) refers to the location of the first minimum outside the main lobe(s) of the signal and is generally smaller than the actual transmission bandwidth and onboard bandpass filtering. Question marks indicate missing or undefined information

Sys	Band	Signal	Frequency (MHz)	BW (MHz)	Ch	Modulation	Rate (MHz)	Code prim./second. (chips)	Type	Data (bps/sps)	Power (min. rcvd.) (dBW)	References
GPS	L1	P(Y)	1575.42	±10	I^+	BPSK(10)	10.23	$6.9 \cdot 10^{12}$	M-seq.	50/50	−161.5	[B.2, 12]
		C/A		±1	Q^+	BPSK(1)	1.023	1023	Gold	50/50	−158.5	[B.2, 12]
		L1C-D		±2	I^+	TMBOC(6,1,4/33)	1.023	10 230	Weil	50/100	−163.0	[B.13]
		L1C-P		±2	I^+	TMBOC(6,1,4/33)	1.023	10 230/1800	Weil	–	−158.25	[B.13]
		M-D		±15	I^+	BOC(10,5) mux	5.115	n/a	n/a	≤100/200	−158.0	[B.11, 14, 15]
		M-P		±15	I^+	BOC(10,5) mux	5.115	n/a	n/a	n/a	−158.0	[B.11, 14, 15]
	L2	P(Y)	1227.60	±10	I^+	BPSK(10)	10.23	$6.9 \cdot 10^{12}$	M-seq.	50/50	$-164.5^{a}, -161.5^{b,c,d}$	[B.2, 12]
		L2 CM		±1	Q^{+e}	BPSK(1) mux	0.5115	10 230	M-seq.	25/50	$-163.0^{b,c}, -161.5^{d}$	[B.2, 12]
		L2 CL		±1	Q^{+e}	BPSK(1) mux	0.5115	767 250	M-seq.	–	$-163.0^{b,c}, -161.5^{d}$	[B.2, 12]
		M-D		±15	I^+	BOC(10,5) mux	5.115	n/a	n/a	≤100/200	−164.0	[B.11, 14, 15]
		M-P		±15	I^+	BOC(10,5) mux	5.115	n/a	n/a	n/a	−164.0	[B.11, 14, 15]
	L5	L5I	1176.45	±10	I^+	BPSK(10)	10.23	10 230/10	M-seq.	50/100	$-157.9^{c}, -157.0^{d}$	[B.16]
		L5Q		±10	Q^+	BPSK(10)	10.23	10 230/20	M-seq.	–	$-157.9^{c}, -157.0^{d}$	[B.16]
GLO	L1	L1SF (P)	$1602.0 + k \cdot 0.5625^{f}$	±5	I	BPSK(5)	5.11	5 110 000	M-seq.	50	n/a	[B.17, 18]
		L1OF (C/A)	$1602.0 + k \cdot 0.5625^{f}$	±0.5	Q	BPSK(0.5)	0.511	511	M-seq.	50	−161.0	[B.19]
	L2	L2SF (P)	$1246.0 + k \cdot 0.4375^{f}$	±5	I	BPSK(5)	5.11	5 110 000	M-seq.	50	n/a	[B.17, 18]
		L2OF (C/A)	$1246.0 + k \cdot 0.4375^{f}$	±0.5	Q	BPSK(0.5)	0.511	511	M-seq.	50	−161.0	[B.19]
	L3	L3OC-D	1202.025	±10	I^-	BPSK(10)	10.23	10 230	Kasami	100/200	?	[B.20, 21]
		L3OC-P	1202.025	±10	Q^-	BPSK(10)	10.23	10 230	Kasami	–	?	[B.20, 21]
	L1	L1SC[g]	1600.955	±5	I^-	BOC(5,2.5)	5.115	?	?	?	?	[B.21, 22]
		L1OC-D[g]	1600.955	±1	Q^-	BPSK(1) mux	0.5115	1023/2	Gold	125/250	?	[B.21, 22]
		L1OC-P[g]	1600.955	±2	Q^-	BOC(1,1) mux	0.5115	1023	Gold	–	?	[B.21, 22]
		L1OCM[h]	1575.42	?	?	?	?	?	?	?	?	[B.24]
	L2	L2SC[g]	1248.06	±7	I^-	BOC(5,2.5)	5.115	?	?	?	?	[B.21, 23]
		L2OC-D[g]	1248.06	±1	Q^-	BPSK(1) mux	?	?	?	?	?	[B.21, 23]
		L2OC-P[g]	1248.06	±2	Q^-	BOC(1,1) mux	0.5115	10 230/50	Kasami	–	?	[B.21, 23]
	L5	L5OCM[h]	1176.45	?	?	?	?	?	?	?	?	[B.24]

Abbreviations: Sys = System; BW = bandwidth; Ch = channel; mux = multiplexed; n/a = nonavailability of public information for regulated/military services

Notes: [a] Block IIA/IIR; [b] Block IIR-M; [c] Block IIF; [d] Block III; [e] Nominal phase relationship, see bit 273 of CNAV msg 10; [f] frequency channel number $k = -7 \ldots +6$; [g] planned; [h] study

Table B.3 (continued)

Sys	Band	Signal	Frequency (MHz)	BW (MHz)	Ch	Modulation	Rate (MHz)	Code prim./second. (chips)	Type	Data (bps/sps)	Power (min. rcvd.) (dBW)	References
GAL	E1	OS-D(B)	1575.42	±2	I^-	CBOC(6,1,1/11)	1.023	4092	rand.	125/250	−160.0	[B.25, 26]
		OS-P(C)		±2	I^-	CBOC(6,1,1/11)	1.023	4092/25	rand.	–	−160.0	[B.25, 26]
		PRS(A)		±17	Q^-	$BOC_{cos}(15,2.5)$	2.5575	n/a	n/a	n/a	n/a	[B.26]
	E6	CS-D(B)	1278.75	±5	I^-	BPSK(5)	5.115	5115	rand.	500/1000	−158.0	[B.25]
		CS-P(C)		±5	I^-	BPSK(5)	5.115	5115/100	rand.	–	−158.0	[B.25]
		PRS(A)		±15	Q^-	$BOC_{cos}(10,5)$	5.115	n/a	n/a	n/a	n/a	[B.26]
	E5ab		1191.795	±25		AltBOC(15,10)[i]						[B.25]
	E5b	E5b-D	1207.14	±10	I^-		10.23	10 230/20	M-seq.	25/50	−158.0	[B.25]
		E5b-P		±10	Q^-		10.23	10 230/100	M-seq.	25/50	−158.0	[B.25]
	E5a	E5a-D	1176.45	±10	I^-		10.23	10 230/20	M-seq.	25/50	−158.0	[B.25]
		E5a-P		±10	Q^-		10.23	10 230/100	M-seq.	25/50	−158.0	[B.25]
BDS-2	B1-2	OS	1561.098	±2	I^+	BPSK(2)	2.046	2046[j], 2046/20[k]	LFSR	250/500[j] 25/50[k]	−163.0	[B.3]
		RS		±2	Q^+	BPSK(2)	2.046	n/a	n/a	n/a	n/a	
	B3	RS	1268.52	±10	I^+	BPSK(10)	10.23	10 230/20	LFSR	n/a	n/a	[B.27, 28]
		RS		±10	Q^+	BPSK(10)	10.23	n/a	n/a	n/a	n/a	
	B2b	OS	1207.14	±2	I^+	BPSK(2)	2.046	2046[j], 2046/20[k]	LFSR	250/500[j] 25/50[k]	−163.0	[B.3]
		RS		±10	Q^+	BPSK(10)	10.23	n/a	n/a	n/a	n/a	
BDS-3	B1-2	OS	1561.098	±2	I	BPSK(2)	2.046	2046/20[k]	LFSR	25/50[k]	−163.0	[B.3]
	B1	B1C-D[l]	1575.42	±2	?	TMBOC(6,1,4/33)	1.023	10 230	?	50/100	?	[B.29, 30]
		B1C-P[l]		±2	?	TMBOC(6,1,4/33)	1.023	10 230/20	?	–	?	[B.29, 30]
		B1A-D[m]		±16	?	BOC(14,2)	n/a	n/a	n/a	50/100	n/a	[B.29, 30]
		B1A-P[m]		±16	?	BOC(14,2)	n/a	n/a	n/a	n/a	n/a	[B.29, 30]
	B3	B3C-D[m]	1268.52	±10	?	BPSK(10)	10.23	n/a	n/a	500/500	n/a	[B.29, 30]
		B3C-P[m]		±10	?	BPSK(10)	10.23	n/a	n/a	500/500	n/a	[B.29, 30]
		B3A-D[m]		±17	?	BOC(15,2.5)	2.5575	n/a	n/a		n/a	[B.29, 30]
		B3A-P[m]		±17	?	BOC(15,2.5)	2.5575	n/a	n/a		n/a	[B.29, 30]
	B2		1191.795	±25	?	TD-AltBOC(15,10)[i]						[B.29–31]
		B2b-D[l]	1207.14	±10	I		10.23	?	?	50/100	?	[B.29–31]
		B2b-P[l]		±10	Q		10.23	?	?	–	?	[B.29–31]
		B2a-D[l]	1176.45	±10	I		10.23	?	?	25/50	?	[B.29–31]
		B2a-P[l]		±10	Q		10.23	?	?	–	?	[B.29–31]

Abbreviations: Sys = System; BW = bandwidth; Ch = channel; LFSR = linear feedback shift register; n/a = nonavailability of public information for regulated/military services; OS = open service; CS = commercial service; PRS = public regulated service; RS = restricted service

Notes: [i] combined signal; [j] GEO; [k] MEO/IGSO; [l] open service (planned); [m] authorized service (planned)

Annex B

Table B.3 (continued)

Sys	Band	Signal	Frequency (MHz)	BW (MHz)	Ch	Modulation	Rate (MHz)	Code prim./second. (chips)	Type	Data (bps/sps)	Power (min. rcvd.) (dBW)	References
QZS-1	L1	C/A	1575.42	±1	I^{+n}	BPSK(1)	1.023	1023	Gold	50/50	−158.5	[B.32, 33]
					Q^{+o}							[B.34]
		L1C-D		±2	I^{+}	BOC(1,1)^{n}	1.023	10 230	Weil	50/100	−163.0	[B.32, 33]
						TMBOC(6,1,4/33)^{o}						[B.34]
		L1C-P		±2	Q^{+n}	BOC(1,1)^{n}	1.023	10 230/1800	Weil	–	−158.2	[B.32, 33]
					I^{+o}	TMBOC(6,1,4/33)^{o}						[B.34]
		SAIF		±1	–	BPSK(1)	1.023	1023	Gold	500/250	−161.0	[B.32]
	L2	L2 CM	1227.60	±1	–	BPSK(1) mux	0.5115	10 230	M-seq.	25/50	−163.0	[B.32, 34]
		L2 CL		±1	–	BPSK(1) mux	0.5115	767 250	M-seq.	–	−163.0	[B.32, 34]
	L6	L61(LEX)^{n}	1278.75	±5	–	BPSK(5) mux	5.115	10 230	Kasami	2000/250	−158.7	[B.32, 35]
				±5	–	BPSK(5) mux	5.115	1 048 575	Kasami	–	−158.7	[B.32, 35]
		L62^{o}		±5	–	BPSK(5) mux	5.115	10 230	Kasami	2000/250	−159.8	[B.35]
				±5	–	BPSK(5) mux	5.115	10 230	Kasami	2000/250	−159.8	[B.35]
	L5	L5I	1176.45	±10	I^{+}	BPSK(10)	10.23	10 230/10	M-seq.	50/100	−157.9^{n}, −157.0^{o}	[B.32, 34]
		L5Q		±10	Q^{+}	BPSK(10)	10.23	10 230/20	M-seq.	–	−157.9^{n}, −157.0^{o}	[B.32, 34]
IRNSS	L5	SPS	1176.45	±24	I^{-}	BPSK(1)	1.023	1023	M-seq.	25/50	−159.0	[B.36, 37]
		RS-D		±16	Q^{-}	BOC(5,2)	2.046	8192	n/a	25/50	−156.0	[B.36, 37]
		RS-P		±16	I^{-}	BOC(5,2)	2.046	8192/40	n/a	–	−159.0	[B.36, 37]
	S	SPS	2492.028	±16	I^{-}	BPSK(1)	1.023	1023	M-seq.	25/50	−162.3	[B.36, 37]
		RS-D		±16	Q^{-}	BOC(5,2)	2.046	8192	n/a	25/50	−159.3	[B.36, 37]
		RS-P		±16	I^{-}	BOC(5,2)	2.046	8192/40	n/a	–	−162.3	[B.36, 37]
SBAS	L1	C/A	1575.42	±1	I	BPSK(1)	1.023	1023	Gold	250/500	−161.0^{p}	[B.11, 38]
		C/A^{q}		±1	Q	BPSK(1)	1.023	1023	Gold	≤250/500	−161.0^{p}	[B.11, 39]
	L5	L5I	1176.45	±10	I	BPSK(10)	10.23	10 230/2	M-seq.	250/500	−161.0^{p}	[B.11, 39]
		L5Q^{q}		±10	Q	BPSK(10)	10.23	10 230/?	M-seq.	≤250/500^{r}	−161.0^{p}	[B.11, 39]

Abbreviations: Sys = System; BW = bandwidth; Ch = channel; mux = multiplexed; n/a = nonavailability of public information for regulated/military services; RS = restricted service; SPS = standard positioning service (open)

Notes: ^{n} Block I; ^{o} Block II; ^{p} Specified minimum received power of all signals; ^{q} Optional signal component; ^{r} Secondary code length varies with selected data rate, product is fixed at 500 bps

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Chapter A.4

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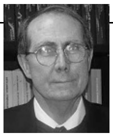

Chapter A.5

Ronald Beard is the former Head of the NRL Advanced Space PNT Branch. In the 1970s, he was the project scientist in the NRL GPS Program Office that developed Navigation Technology Satellites 1 and 2, which operated the first atomic clocks in space. He became the Program Manager of the NRL GPS Clock Development program in 1984 and Precise Time and Time Interval (PTTI) technology for military navigation and communication systems.

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Chapter B.8

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Oliver Montenbruck Chaps. A.1, A.2, A.3, B.8, B.10, B.11, C.17, E.32; Annexes A, B For biographical profile, please see the section “About the Editors”.

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Detailed Contents

5 Clocks

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Detailed Cont.

Glossary of Defining Terms

A

Accuracy
A measure for the closeness of a measured or estimated quantity to the quantity's true value.

Acquisition
The process carried out by a GNSS receiver to identify which GNSS signals are present in the received signal and to determine an approximate code delay and Doppler shift of those signals.

Aircraft Based Augmentation System (ABAS)
A GNSS augmentation system that augments and/or integrates the information obtained from the other GNSS elements with information available on board the aircraft.

Airport Pseudolite (APL)
A ► *pseudolite* located within the boundary of an airport designed to augment the positioning geometry of aircraft approaching or traveling near that airport.

Albedo
A measure for the reflectivity of a body. Earth albedo is a source of indirect radiation pressure acting on a satellite (► *Earth Radiation Pressure*).

Alert
A timely warning that a system may no longer be operating as previously described and that it could now be providing misleading information.

Alert Limit
A maximum tolerable positioning error for an operation to safely proceed. An alert limit has an associated ► *integrity* risk probability and a maximum time before the user must be notified when the alert limit cannot be assured to that integrity risk level.

Allan Deviation (ADEV)
The square-root of the ► *Allan Variance*.

Allan Variance (AVAR)
A measure of clock stability named after the physicist David W. Allan. It describes the variance of the average clock frequency over different time scales not taking into account constant frequency errors.

Almanac
A set of coarse orbit parameters for an entire GNSS constellation that is transmitted as part of the ► *navigation message* by each satellite of the constellation. The almanac facilitates rapid acquisition of all visible satellites.

Alternative BOC (AltBOC)
A modulation scheme combining two quadrature phase shift key signals in adjacent frequency bands, into a combined wideband signal with superior ► *noise* and ► *multipath* properties. AltBOC modulation was first employed for the Galileo E5a/E5b signal.

Ambiguity Dilution of Precision (ADOP)
A scalar measure in cycles that captures the intrinsic precision of the estimated float ambiguity vector. The ADOP is invariant for ambiguity re-parameterizing ► *Z-transformations* and facilitates easy-to-compute approximations of the ambiguity success rate.

Ambiguity
The initial unknown offset in a carrier phase observation when a GNSS receiver first locks onto a GNSS signal. It is the sum of the initial phase and the integer ambiguity. The ambiguity value remains constant as long as the receiver remains locked on the signal.

Ambiguity Fixed Solution
An integer ambiguity resolved GNSS parameter solution. The precision of the ambiguity fixed solution is never poorer than that of the ► *ambiguity float solution*.

Ambiguity Float Solution
A GNSS parameter solution for which the ambiguities are not resolved as integers. The precision of the ambiguity float solution is never better than that of the ► *ambiguity fixed solution*.

Ambiguity Resolution
► *Integer ambiguity resolution*

Ambiguity Success Rate
The probability of correct ► *integer ambiguity* estimation.

Anechoic Chamber
A room or cabinet, the interior of which is non-reflective, absorbing radio-frequency signals originating from within the chamber. In many cases it is often desirable that it also contains these signals and isolates the interior from externally originating signals. Typically used when it is necessary to model an infinite, reflector free space, when conducting a broadcast test, or in cases where the test must be isolated from external interference, or when the test involves the broadcast of signals in protected or restricted bands.

Antenna
A hardware unit that converts electrical energy to electromagnetic waves or vice versa.

Antenna Gain Pattern
A direction-dependent measure of the antenna's efficiency to convert electrical power into radio waves (transmit antenna) or vice versa (receiving antenna).

Antenna Phase Center
The point in the antenna radiation pattern where all the field emanates from or converges to.

Antenna Reference Point
A well defined and easily accessible mechanical point of the antenna to which the electrical ► *antenna*

phase center can be referred and which can itself be referred to the marker of a geodetic monument.

Antenna Thrust
The recoil force due to transmission of GNSS microwave signals which causes a non-gravitational acceleration of the satellite.

ANTEX
The antenna exchange format is used by the IGS to distribute a consistent set of absolute ► *antenna phase center* corrections for both GNSS receivers and satellites. Includes both ► *phase center offsets* and ► *phase center variations*.

Anti-spoofing (A/S)
The use of signal encryption for the military ► *P-code* of the ► *Global Positioning System* to avoid the generation and transmission of spoofed signals by an enemy (► *spoofing*).

Apogee
The most distant point of a satellite orbit from the Earth.

Apogee Kick Motor
An onboard rocket that is used to place a satellite in its final orbit from a highly elliptical transfer orbit.

Approach Procedure with Vertical guidance (APV)
An instrument approach procedure with both lateral and vertical guidance supporting operations with a performance that is between non-precision and precision approach.

Area Correction Parameters
► *Flächenkorrekturparameter*

Area Navigation (RNAV)
RNAV is a method of navigation which permits the operation of an aircraft on any desired flight path. It allows its position to be continuously determined wherever it is rather than only along tracks between individual ground-based navigation aids.

Ascending Node
The point on an orbit at which a satellite crosses the Equator from south to north.

Astronomical Unit
A unit of length that is used to specify distances within the Solar System. One astronomical unit (AU) is approximately equal to the mean distance between the Earth and the Sun, and amounts to roughly 149.6 Mio. km.

Atmosphere
The shells of gases that surround the Earth. The atmosphere affects the motion of satellites in low Earth orbit (► *drag*) and the radio propagation of electromagnetic waves such as radio navigation signals (► *troposphere*, ► *ionosphere*).

Atomic Clock
A device using the frequency of an electronic transition of atoms to generate a timescale. Atomic clocks are the most stable time and frequency standards known.

Atomic Fountain
A signal generator/frequency standard based on the laser cooling of atoms in a magneto-optical trap and once cooled to near absolute zero conditions, they are launched upwards in the gravity field in a *fountain* arrangement. In this manner the atoms pass through an interrogation region that stimulates a hyperfine transition of the atom's ground state.

Atomic Frequency Standard
A signal generator based on the interrogation of the change in a particular energy state of a specific atom contained in a controlled environment.

Atomic Time Scale
A time scale based on atomic or molecular resonance phenomena. Elapsed time is measured by counting cycles of a frequency locked to an atomic or molecular transition. Atomic time scales differ from the earlier astronomical time scales, which define the second based on the rotation of the Earth on its axis. ► *Coordinated Universal Time* (UTC) is an atomic time scale, since it defines the second based on the transitions of the cesium atom.

Attitude
The orientation of a rigid body in space with respect to a given reference frame. The attitude can be expressed in various forms of ► *attitude parameters*.

Attitude Parameters
The set of variables used to parameterize the orientation of a rigid body in space. Their number ranges from three (e.g., ► *Euler angles*) to nine (e.g., ► *direction cosines*).

Automatic Dependent Surveillance (ADS)
A surveillance technique where each aircraft automatically broadcasts its own position periodically via data-link.

Automatic Direction Finding (ADF)
an electronic aid to navigation that identifies the relative bearing of an aircraft from a radio beacon transmitting in the medium or long-frequency bandwidth, such as a ► *Non Directional Beacon* or commercial radio broadcast station.

Availability
The probability that a user is able to determine its position with the specified accuracy and is able to monitor the integrity of its determined position at the initiation of the intended operation.

Azimuth
One of the coordinates in the ► *horizontal system*. Azimuth is the angle, measured positive towards the east, between north and the projection on the horizon of the direction in which an object is observed.

B

Bandwidth
The range of frequencies that pass through a system without (significant) attenuation.

Barycentric System
A coordinate system whose center (origin) is at the average center-of-mass of the solar system.

Baseband
The frequency range used by conventional transmitters or receivers for performing pre/post-processing of the desired information.

Baseband Signal
A signal with a near-zero frequency and low bandwidth, such as the GNSS spreading code and data modulated onto the carrier signal. Also termed the envelope signal.

Baseline
The separation between two points in 2-D or 3-D space. For ► *differential positioning* the baseline refers to the 3-D vector between two GNSS receivers, one set up on a ► *base station*, the other at a point (or in space) whose coordinate is to be determined relative to the ► *base station*. Baseline length is a scalar quantity, being the inter-receiver distance expressed in length units.

Base Station
► *Reference station*

BeiDou
A regional and global navigation satellite system implemented by China. The name refers to the constellation (Big Dipper or Plough) used to find the north direction in stellar navigation.

BeiDou Satellite-based Augmentation System (BDSBAS)
A ► *satellite-based augmentation system (SBAS)* being developed as part of the BeiDou Navigation Satellite System to provide horizontal and vertical navigation throughout China.

Best Linear Unbiased Estimator (BLUE)
The estimator with the best precision, i. e., smallest variance, of all linear unbiased estimators. Linear unbiased estimators are linear functions of the observables that have an expectation equal to the to-be-estimated unknown parameter vector.

Best Linear Unbiased Predictor (BLUP)
The predictor having the smallest mean square prediction error (best) of all linear unbiased predictors. Linear unbiased predictors are linear functions of the observables that have an expectation equal to the expectation of the to-be-predicted random parameter vector.

Between-receiver Difference
Difference between (code or carrier-phase) GNSS observations or parameters at the same frequency for two receivers tracking the same satellite.

Between-satellite Difference
Difference between (code or carrier-phase) GNSS observations or parameters at the same frequency of two satellites that are tracked by the same receiver.

Bias
In estimation, *bias* denotes the difference between the expected value of an estimator and the true value being estimated. Biases are often the consequence of an improper modeling of measurement processes, such as the neglect of non-negligible systematic errors. More loosely and generally, the term is often used to describe a systematic error or offset in a measurement.

Bias-to-noise Ratio (BNR)
A dimensionless measure of bias significance. The influential-BNR drives the probability of hazardous occurrence, while the testable-BNR drives the probability of missed detection.

Binary Offset Carrier (BOC) Modulation
An extension of ► *binary phase shift keying (BPSK) modulation*, in which the modulated signal is multiplied by an additional sine or a cosine square wave sub-carrier. Instead of a single lobe, the spectrum of a BOC-modulated signal exhibits two main lobes symmetrically shifted relative to the main carrier frequency. Therefore, BOC modulation is also known as a split-spectrum modulation. The separation of the two lobes is determined by the sub-carrier frequency. In GNSS, BOC signals are applied in order to fulfill spectral separation requirements between non-interoperable signals of different systems.

Binary Phase Shift Keying (BPSK) Modulation
A modulation scheme for radio navigation signals, in which the phase of the carrier is shifted by 0° or 180° depending on the binary value of the modulated signals (i. e., ranging code and navigation data).

Bit Error Correction
The process carried out within a GNSS receiver to identify and correct incorrectly received ► *navigation message* bits. This process requires the navigation message to contain redundant bits.

Bit Synchronization
The process carried out within a GNSS receiver to identify the epochs of navigation data bit/symbol transitions if the bit/symbol duration exceeds the primary code duration.

Blunder
A gross error in a measurement that is neither systematic nor of random nature.

Block
Different generations of Global Positioning System (GPS) satellites built by different manufacturers are commonly termed *blocks*. The second generation is further divided into Block II, IIA, IIR, IIR-M, and IIF satellites.

Boresight Angle
The angle between the line-of-sight direction and the symmetry axis of an antenna.

Boundary Layer
The lowermost atmospheric layer directly affected by the Earth's surface.

Box-wing Model
A simplified description of geometrical and optical (reflection/emission) properties of a GNSS satellite for the modeling of ► *radiation pressure* effects.

Broadcast Ephemeris
The ► *ephemeris* transmitted by a GNSS satellite as part of its ► *navigation message* to enable computation of the satellite positions within a receiver.

Broadcast Group Delay (BGD)
Alternative name for ► *Timing Group Delay (TGD)*.

C

C-band
The part of the spectrum of electromagnetic waves with carrier frequencies in the range from 4 GHz to 8 GHz

C/A-code
The ► *pseudo-random noise (PRN)* sequence used as coarse and acquisition ranging code within the Global Positioning System GPS. Each C/A-code has a length of 1023 chips and is transmitted in 1 ms. An entire family of C/A-codes has been defined for GPS as well as other radio navigation systems such as SBAS and QZSS. The serial number assigned to each code known as the PRN number and commonly used to identify the transmitting GPS satellite.

Cadastral Surveying
A form of land surveying for the determination, or marking-out of land property boundaries.

Carrier
A periodic electromagnetic wave on which the ranging code and navigation data of a radio navigation satellite system are modulated. GNSS signals are commonly located in the ► *L-band* and employ frequencies in a range of about 1100–1600 MHz.

Carrier Phase
The instantaneous phase (expressed in radians or cycles) of a periodic electromagnetic wave. In GNSS the term is commonly related to the beat phase of the received carrier after mixing with the nominal signal frequency, which represents a measure of the range variation between the transmitting satellite and the receiver.

Carrier Phase Ambiguity
The measurement of the ► *carrier phase* inside a GNSS receiver includes an arbitrary cycle count introducing an integer-cycle ambiguity. Depending on the specific tracking technique, half-cycle biases may also arise. The measured carrier phase range is furthermore affected by satellite or receiver specific biases causing a float-valued ambiguity in the measured carrier phase range.

Carrier-to-noise Density Ratio (C/N_0)
The ratio of the power level of the carrier signal to the noise power within a 1 Hz bandwidth.

Celestial Coordinates
Spherical coordinates of celestial objects with respect to a celestial reference system, called ► *right ascension* and ► *declination*, analogous to longitude and latitude, respectively.

Celestial Ephemeris Pole
The reference pole for ► *nutation* and ► *polar motion* that was adopted by the 1980 IAU theory of nutation. By definition, it is a pole that exhibits no nearly diurnal motions in either the celestial or terrestrial reference frames.

Celestial Intermediate Pole
The reference pole for ► *nutation* and ► *polar motion* that was adopted by the 2000 IAU theory of nutation. It extends the definition of the ► *celestial ephemeris pole* by clarifying the distinction between nutation and polar motion. Motion of the celestial intermediate pole within the celestial reference frame that has a frequency between -0.5 cycles per sidereal day (cpsd) and +0.5 cpsd is defined to be nutation. Motion of the celestial intermediate pole outside this frequency band is defined to be polar motion. The polar motion parameters reported by Earth rotation measurement services give the location of the celestial intermediate pole within the rotating, body-fixed terrestrial reference frame.

Celestial Sphere
An imaginary sphere of infinite radius on which radial direction are projected. The center of the celestial sphere may be viewed as being geocentric or barycentric, depending on the definition of the associated coordinate system.

Central Synchronizer
The master clock of the GLONASS system. It comprises four ► *hydrogen maser* frequency standards and contributes to the mathematical GLONASS System Time steered to UTC(SU).

Certification
A process applied by a regulating body to determine whether an object has been manufactured according to an approved design and that the design ensures compliance with previously specified requirements. The requirements are often specified in ► *Minimum Operating Performance Standards (MOPS)* and related documents.

Cesium Beam Frequency Standard
A signal generator based on the hyperfine frequency of the cesium atom's ground state of 9 192 631 770 Hz. Typically, the cesium atoms are thermally formed into a beam and magnetically separated into the ground state for interrogation.

Chandler Period
A characteristic period in the oscillation of the Earth's rotation axis relative to its axis of figure discovered by S.C. Chandler. Due to the non-rigid structure of the Earth, the Chandler period may vary in a range of about 412–442 days.

Chapman Profile
An analytical model describing the height-dependent electron density variation in the ionosphere or its individual layers based on simplifying assumptions of the atmospheric structure as well as the ionization and recombination processes.

Chinese Area Positioning System (CAPS)
A positioning system developed in China, which transfers ground-generated navigation signals to users via communication satellites.

Choke-ring Antenna
An ► *antenna* composed of the sensitive antenna element and a surrounding, corrugated ground plane, which is typically made up of multiple concentric conductive rings. Choke ring antennas offer superior ► *multipath* suppression and are commonly used for

the highest accuracy user applications such as for geodetic surveys or ► *continuously operating reference stations*.

Circular Error Probable (CEP)
The radius of a circle centered on the true value that contains 50% of the actual measurements.

Clock Ensemble
A collection of clocks, not necessarily in the same physical location, operated together in a coordinated way to maximize the performance (time accuracy and frequency stability) and/or the availability of a time scale. Typically, the relative value of each clock is weighted, so that the best clocks contribute the most to the average.

Clock Offset
The offset between the reading of a satellite or receiver clock involved in the timing of GNSS measurements and a given reference time scale, such as the system time maintained by the GNSS control segment.

Coarse/Acquisition (C/A) Code
► *C/A-code*

Code Bias
A receiver and transmitter specific hardware ► *group delay* affecting the ► *pseudorange* (i. e., code observation) generation.

Code Division Multiple Access (CDMA)
A multiple access scheme that allows different transmitters to access the transmission channel simultaneously using the entire available bandwidth where the transmitter is identified by a unique code assigned to it. CDMA signals form the basis of most navigation satellite systems in use today.

Code Phase
The instantaneous phase of the ranging code modulated on a GNSS signal as sensed by a receiver. It can be expressed as the number of full and fractional code chips, or, alternatively as a time or distance value. The code phase is a measure of the transmission time (modulo the code duration) and used together with the current receiver time to form a ► *pseudorange* measurement.

Code Shift Keying (CSK)
A specific scheme used to increase the rate of navigation data in a GNSS signal. The ranging code is shifted relative to a nominal starting point by an amount that is determined by the encoded data word. Code shift keying is, for example, employed in the E6 signal of the Japanese ► *Quasi-Zenith Satellite System (QZSS)* to transmit high-rate correction data for ► *precise point positioning* to its users.

Coherent Integration Time
The time period chosen by a GNSS receiver to compute correlation values of the received signal with internal replica signals.

Cold Start
Activation of a GNSS receiver with no prior information on time, user position, and satellite orbit/clock data.

Compatibility
The ability of two navigation signals to be transmitted and used along each other without causing harmful interference for their users.

Conductive Test
Testing a receiver by directly connecting a signal source to the receiver.

Constrained Maximum Success-rate (CMS) Test
An ambiguity acceptance test which has the largest success rate for a given user-defined failure rate. This test requires the ► *integer least-squares (ILS)* solution as its input.

Construction Surveying
Land surveying that addresses the different positioning requirements of civil engineers and building professionals during the construction phase for any engineered structure.

Conterminous (or Contiguous) United States (CONUS)
The 48 adjoining US states and Washington, DC. CONUS is the portion of the United States that excludes Alaska, Hawaii, and all offshore territories.

Continental Drift
► *plate motion*

Continuity
The probability that a user is able to determine its position with the specified accuracy and is able to monitor the integrity of its determined position over the time interval applicable for the corresponding phase of flight. Assuming the service is available at the start of an operation, this is the probability of it becoming unavailable over a specified time interval linked to the duration of the operation.

Continuously Operating Reference Stations (CORS)
A GNSS receiver and antenna established on a permanent and stable site that serves as a ► *control point* of a geodetic network or reference station for ► *differential GNSS* systems.

Controlled Flight into Terrain (CFIT)
The situation when a normally functioning aircraft under the complete control of the pilot is inadvertently flown into an obstacle.

Control Point
A marker or monument used for surveying, typically with known coordinates in the local or national geodetic ► *datum*. May also be a ► *base station* if a GNSS receiver is operated at that point.

Control Segment
The ground infrastructure used to operate a global or regional navigation satellite system.

Coordinated Universal Time
► *Universal Time Coordinated (UTC)*

Coordinate Time (TCB,TCG)
A set of fundamental relativistic time scales with rates based on the SI second in the respective reference frames, i. e., at the Solar System's center of gravity for Barycentric Coordinate Time (TCB) and the Earth's center for Terrestrial Coordinate Time (TCG).

Correlation
A measure of agreement between two statistical values or time series. In estimation, correlation is

defined as a normalized form of the ► *covariance*. In GNSS signal processing, the correlation describes how well two signals or ► *pseudo-random noise* codes match each other.

Correlator
A device used inside a GNSS receiver to measure the ► *correlation* of the incoming signal and a receiver-generated replica. The correlator values serve as input for the ► *tracking loops*, which aim to continuously align the replica code and phase with the incoming signal. In order to best measure the instantaneous code offset, a combination of an *early* and a *late* correlator is used, which employ time shifted code replicas. The early-minus-late difference of the correlator outputs can then be used as a ► *discriminator* to sense the tracking error.

Correlator Spacing
The spacing (in units of PRN chips) between the early and late ► *correlators* in a conventional ► *delay lock loop*.

Coseismic
means *during an earthquake*. The term is most commonly used to describe displacements that result from an earthquake.

COSPAS-SARSAT
An international satellite-based search and rescue system.

Costas Loop
A special form of a ► *phase lock loop* developed by J.P. Costas that uses a two-quadrant phase discriminator to track a signal with ► *binary phase shift keying (BPSK) modulation* without being affected by data bit transitions.

Covariance
A measure of how much two random variables change together. ► *Correlation* is the normalized version of covariance. It is obtained by dividing the covariance by the standard deviations of the two random variables.

Cramer Rao Lower Bound (CRLB)
A lower bound on the variance of unbiased estimators of deterministic parameters. Named after H. Cramer and C.R. Rao

Cross-correlation
Operation on two (real or complex) Doppler and delay-aligned signals to estimate their temporal coherence, as a function of the relative delay. Such function is termed waveform.

Cycle Slip
An unknown discontinuity in the measured ► *carrier phase* usually resulting from a temporary loss-of-lock (e.g., due to shading) in the carrier tracking loop of a GNSS receiver.

D

Data Bit
The basic information unit of the navigation message modulated on a GNSS signal. This unit is called symbol, if the navigation message employs a ► *forward error correction* scheme. Otherwise it is called bit.

Data Channel
A GNSS signal component used to broadcast navigation data. For improved measurement performance, the data channel is complemented by a ► *pilot signal* in modern GNSS signals.

Data Demodulation
The process carried out within a GNSS receiver to extract a data bit or data symbol from a received GNSS signal.

Data Snooping
A procedure to identify the observations contaminated with gross errors.

Data Symbol
► *data bit*

Datum
A set of parameters and conventions that defines and realizes a coordinate system for geodetic control on a national or global scale. Nowadays realized by the 3-D Cartesian coordinates or 2-D geodetic coordinates of a network of ► *control points*.

Decision Altitude or Height (DA/H)
The altitude or height during an instrument approach procedure where the pilot must decide to either continue the approach to land or initiate the missed approach procedure. The decision is based on the availability of the required visual references. The decision altitude is measured above mean sea level and a decision height is above the ground. The DA/H is the point at which a missed approach is initiated and does not preclude the aircraft from descending below this height before the aircraft starts to climb.

Declination
The angle, at right-angles to the ► *equator*, measured between the equator and a celestial body. Together with ► *right ascension*, declination forms the equatorial system of coordinates.

Deflection of the Vertical
The angle between the tangent to the plumb line (direction of gravity) and the normal to the ellipsoid at a point.

Deformation
Any displacement that changes the shape of a body, as opposed to rigid body motion. Active tectonic and volcanic processes cause both recoverable and permanent deformation of the Earth.

Delay Lock Loop (DLL)
A controller used within a GNSS receiver to align a replica of the ranging code with the incoming signal after removal of the carrier. The DLL combines a steerable code generator with a code ► *discriminator* to sense the tracking error and a loop filter to reduce the tracking noise.

Differential Code Bias (DCB)
Difference of either receiver or satellite hardware biases on the code (or ► *pseudorange*) observations of two frequencies.

Differential GNSS (DGNSS)
GNSS positioning technique based on the principle that common biases between receivers can be eliminated or significantly reduced by processing multi-receiver code (pseudorange) and/or carrier-phase data simultaneously tracked from the same satellites. At least two receivers are needed; one is the reference and the other rover. This technique can be implemented either by differencing the observations of reference and rover, or by transmitting corrections determined at the reference to the rover.

Dilution of Precision (DOP)
A scalar measure that captures the impact of the instantaneous receiver-satellite geometry on the precision of ► *single point positioning*. It is computed as the square root of the sum of those diagonal elements of the variance matrix excluding the variance factor for which the DOP needs to be evaluated (e.g., Position DOP based on the diagonal elements for east, north and up and horizontal DOP when only the diagonal elements for east and north are involved, etc.).

Direct Conversion
A method to digitize a radio frequency signal without prior down-conversion.

Direction Cosine
the cosine of the angle formed by a vector in space and a reference direction.

Discriminator
A function of ► *correlator* values used to measure the code, phase, or frequency offset between the incoming GNSS signal and the replica generated in the receiver.

Dispersive Medium
A medium in which an electromagnetic wave propagates for which the magnetic constant (permeability) and/or the dielectric constant (permittivity) depend on frequency. Therefore, the phase velocity as well as the group velocity of an electromagnetic wave in a dispersive medium also depend on frequency.

Displacement
The change in position of a point. All points on the Earth's surface are displaced slowly and steadily by plate motions, but sudden displacements also can occur due to events such as earthquakes. Seasonal movements of mass cause quasi-periodic displacements due to loading.

Disposal Orbit
An orbit for satellites that are beyond the end of their service life, which is designed to minimize the probability of a collision with any other satellites or space debris.

Distance Measuring Equipment (DME)
A combination of ground and airborne equipment which provides a continuous slant range distance-from-a ground station by measuring the propagation delay of a signal transmitted by the aircraft to the station and responded back. The ground equipment is a VHF transmitter and receiver (called the transponder) and the airborne equipment is called the interrogator.

Doppler/Delay Alignment
Operation to compensate the delay experienced by a signal due to the relative motion of the transmitter and the receiver. For a short time interval the relative motion can be modeled using two quantities, the initial relative delay and the initial relative Doppler.

Doppler Delay Map (DDM)
An evaluation of the ► *cross-correlation* function of the received signal with a replica signal expressed as a function of code delay and ► *Doppler shift*.

Doppler Effect
► *Doppler Shift*.

Doppler Range
The range of frequency offsets from the nominal signal frequency considered by a GNSS receiver in the signal search to account for the Doppler shift due to the relative motion of transmitter and receiver as well as the frequency error of the local oscillator.

Doppler Shift
The frequency shift experienced by an electromagnetic (or acoustic) wave due the relative motion of the transmitter and receiver. Named after the Austrian nineteenth-century physicist Christian Doppler.

Double-difference
Difference between either two ► *between-receiver differenced* observations/parameters that correspond to different satellites, or two ► *between-satellite differenced* observations/parameters that correspond to different receivers.

Down-conversion
A method to convert the frequency of a radio-frequency signal to a reduced intermediate frequency by mixing it with a harmonic signal. Down-conversion facilitates the analog-to-digital conversion and the subsequent signal processing.

Draconitic Period
The time that elapses between two passages of the orbiting object through its ► *ascending node*.

Draconitic Year
The repeat period of the orientation of a GNSS constellation with respect to the Sun, e.g., 351.5 days for GPS.

Dual-frequency
The use of GNSS measurements on two different signal frequencies, e.g., to eliminate the impact of ionospheric path delays.

Dynamical Time (TDB, TDT)
A relativistic time scale having a rate that matches the SI second at the Earth's surface, defined as a re-scaling of the ► *Coordinate Time scales TCG and TCB*. In 1991 it was agreed by the International Astronomical Union that Terrestrial Dynamical Time (TDT) should just be called ► *Terrestrial Time (TT)*.

E

Early-minus-late Correlator
► *correlator*

Earth-centered Earth-fixed (ECEF)
Refers to a coordinate system or frame that is fixed to the Earth's crust with a conventional orientation and whose origin is at the Earth's center of mass. The axes of the ► *International Terrestrial Reference Frame* provide a possible choice of an ECEF coordinate system.

Earth-centered Inertial (ECI)
A non-accelerating, non-rotating frame aligned with the ► *Earth-centered Earth-fixed (ECEF)* frame at a specific instant of time. Various approximate ECI frames may be convenient for analysis. For example, the non-rotating ECI frame origin may be assumed to coincide with the ECEF origin, which is approximate because the ECEF origin is accelerating.

Earth Model PZ-90
► *Parametry Zemli 1990 (PZ-90)*

Earth Oblateness
The oblateness or ► *flattening* is a measure of how much the Earth's elliptical shape differs from a sphere.

Earth Orientation Parameters
A set of parameters that relate an Earth-centered Inertial coordinate system to an Earth-centered Earth-fixed coordinate system and vice versa. It consists of the small angles that define the motion of the ► *Celestial Intermediate Pole* (approximately Earth's instantaneous spin axis) with respect to the terrestrial reference system (► *polar motion*) and its motion relative to the celestial reference system (► *precession* and ► *nutation*).

Earthquake Cycle
The roughly cyclic buildup of stress and strain and their release in earthquakes is termed the earthquake cycle. The shallow part of most faults is stuck together (locked) by friction most of the time, while the deeper part continues to creep at a nearly steady rate. This causes an increase in the stress around the locked fault zone and results in elastic strain energy being stored in the crust. When the driving stress exceeds the frictional resistance, the fault slips and an earthquake occurs. Earthquakes are never perfectly periodic in occurrence, so this should not be understood to be a periodic process.

Earth Radiation Pressure
The non-gravitational force acting on a satellites due to radiation reflected/emitted by the Earth's surface (► *Albedo*).

Earth Rotation Angle
The angle between the origins on the intermediate terrestrial and celestial equators; it is proportional to the time associated with Earth's rate of rotation.

Ecliptic
The imaginary great circle representing the intersection of the plane of the Earth's orbit with the celestial sphere.

Effective Isotropic Radiated Power (EIRP)
The amount of power radiated by an antenna in a particular direction as referenced to the amount of power fed to an idealized lossless isotropic antenna that would produce the same power density.

Elevation
The angle measured from the observer's horizontal plane with respect to the station-satellite line-of-sight. May also refer to a station's height in metric units with respect to the zero datum level, or synonymous with ► *ellipsoidal height*.

Elevation Mask
A threshold controlling the allocation of GNSS for tracking in the receiver or for processing in the positioning. Only satellites exceeding the defined minimum angle above the ► *horizon* (or alternatively the antenna ground plane) will be considered.

Ellipsoid
In geodesy, it generally refers to a geometric figure defined by rotating an ellipse about its minor axis and whose parameters (size and flattening) are chosen to yield a good approximation to the geoid. It is the mapping surface for horizontal geodetic control. It is also called a spheroid to distinguish it from a more general tri-axial ellipsoid.

Ellipsoidal Height
The distance along the perpendicular (normal) to an ellipsoid starting from the ellipsoid. Ellipsoidal height is positive for points outside the ellipsoid and negative for points inside the ellipsoid, being zero on the ellipsoid.

Elongation
The angle between two bodies, as seen by an observer.

Empirical CODE Orbit Model (ECOM)
A model for solar ► *radiation pressure* developed at the Astronomical Institute of the University Bern, a member of the Center for Orbit Determination in Europe (CODE). The radiation pressure is modeled with constant and sine/cosine terms in a Sun-oriented system.

Ephemeris
Based on a Greek expression (*for a single day*), the term is widely used for astronomical tables giving the daily coordinates of a planet or other solar system body. In GNSS, ephemerides are likewise tabular positions and clock offsets of the GNSS satellites (resulting, e.g., from a ► *precise orbit determination*). Furthermore, the term ephemeris is used for a set of orbital parameters transmitted by a GNSS satellite as part of its ► *navigation message* to enable computation of the satellite positions within a receiver.

Ephemeris Time (ET)
An astronomical time defined by the orbital motions of the Earth, Moon, and planets. Ephemeris Time was introduced in 1952 to be provide a time scale independent of the irregular, unpredictable variations in the rotation of the Earth, inherent to the ► *Universal Time* in use beforehand. Within the framework of relativistic theories of motion, Ephemeris Time has been replaced by ► *Terrestrial Time (TT)*.

Equator
An imaginary great circle on the celestial sphere, which is perpendicular to the Earth's axis of rotation. The equator separates the northern and southern

celestial hemispheres, and is simultaneously the reference plane for the equatorial system of coordinates, which uses the coordinates ► *right ascension* and ► *declination*. It defines the plane that is orthogonal to the polar axis of a global coordinate system. For the Earth it is the circle on the ellipsoid at zero latitude.

Equatorial Coordinates
Coordinates referred to the ► *equator* (► *right ascension*, ► *declination*).

Equinox
► *vernal equinox*.

Euler Angles
A set of three angles that define the orientation of a rigid body. The Euler angles define a sequence of three consecutive rotations that enable aligning any two arbitrarily rotated orthogonal frames.

Euler Axis and Angle
The rotation axis and rotation angle of a body in space relative to an initial or reference orientation. Any rotation of a rigid body in space can be described in terms of an axis-angle parameterization.

European Geostationary Navigation Overlay Service (EGNOS)
A ► *satellite-based augmentation system (SBAS)* developed by the European Space Agency, the European Commission, and EUROCONTROL to provide horizontal and vertical navigation throughout Europe. It has provided safety-of-life service since 2011.

Expandable Slot
In the GPS constellation, one of three orbital positions that can each be divided into a pair of positions when the constellation has more than the nominal number (24) of satellites.

Extended Kalman Filter (EKF)
The ► *Kalman filter* applied to the linearized versions of non-linear state space measurement and dynamic models.

F

Fading Frequency
The phase rate-of-change (known simply as phase rate) of a multipath signal relative to the direct-path signal.

Fixed Solution
► *ambiguity fixed solution*

Fixed Failure Rate Ratio Test
An ambiguity acceptance test that is computed as a ► *ratio test*, but that has a guaranteed failure rate. The required failure rate can be set by the user.

Flächenkorrekturparameter (FKP)
Original German designation of area correction parameters (horizontal gradients) of regional models for distance-dependent biases transmitted to the users as part of ► *network RTK corrections*.

Flattening
The geometric parameter of an oblate ► *ellipsoid* defined by the ratio of the difference between semi-major and semi-minor axes of an ellipsoid to its semi-major axis.

Flicker Noise
A type of noise in electronic systems (e.g., oscillators), which exhibits a power spectral density inversely proportional to the frequency.

Flight Management System (FMS)
An aircraft computer system with multiple functions for managing a flight. The FMS includes navigation and guidance functions and contains a database allowing flight plans and routes to be pre-programmed.

Flight Technical Error (FTE)
The difference between the estimated position and the defined path. It serves as a measure of how well the pilot or the avionics can follow the guidance information provided by the navigation system.

Float Solution
► *ambiguity float solution*.

Footprint
The region beneath a satellite that can receive and utilize its signal. A navigational satellite footprint is often depicted as a circular region directly below the satellite representing a set of users whose line of sight to the satellite is at least 5° above their local horizon.

Forecast
A forecast describes the future state and/or development of characteristic system parameters like the temperature in the troposphere or the electron density in the ionosphere based on the current state and additional information.

Forward Error Correction (FEC)
A technique used to minimize bit errors in data transmission which introduces redundant information into the data stream. Other than simple parity checksums, FEC enables not only detection but also correction of errors.

Frame Bias
A small constant angular offset between the current kinematic ICRF pole and origin (in right ascension) and the dynamic pole and equinox of J2000.

Frame synchronization
The process carried out within a GNSS receiver to identify the beginning of the navigation data message.

Free-space Loss
The change in signal power of an electromagnetic wave emerging from an isotropic radiator when propagating in free space. The free-space loss grows with the square of the distance and is inversely proportional to the square of the wavelength.

Frequency
The rate of a repetitive event, i. e., the inverse of its repeat period. In the SI system of units the period is expressed in seconds (s), and the frequency is expressed in Hertz (Hz).

Frequency Lock Loop (FLL)
A controller used to align the frequency of a carrier replica inside a GNSS receiver with that of the incoming signal. It comprises a ► *numerically controlled oscillator (NCO)*, a frequency

► *discriminator* that senses the instantaneous tracking error and a loop filter that provides a smoothed estimate of the frequency error for feedback to the NCO.

Frequency Division Multiple Access (FDMA)
A multiple access scheme that allows different transmitters to access the channel simultaneously but using slightly different frequencies within the specified overall bandwidth. For global satellite navigation systems, FDMA signals are presently only used by ► *GLONASS*

Friis Formula
A formula named after the electrical engineer H.T. Friis, which is widely used in communications to calculate the total noise factor of a cascaded stage radio frequency ► *frontend* of which each stage is represented by a noise factor and a gain.

Frontend
The combination of different modules that convert the incoming ► *baseband signal*, on the transmitter side, to the specified radio frequency before passing it on to the antenna. A receiver frontend does the opposite.

G

Galileo
The European global navigation satellite system.

Galileo-GPS Time Offset (GGTO)
As GPS and Galileo use different reference time systems, there is a system time offset between the two systems, the Galileo-GPS time offset. This offset can be several tens of nanoseconds or tens of meters. Users can correct their data for the offset, since the GGTO is broadcast as part of the navigation messages.

Geocentric Coordinates
Coordinates referred to the center of the Earth.

Geodetic Coordinates
Coordinates of latitude, longitude, and height associated with a particular ► *ellipsoid*. The geodetic latitude is the angle of the ellipsoid normal for a point relative to the Equator. The geodetic longitude is the same as the spherical longitude. See also ► *ellipsoidal height*.

Geodetic-grade Receiver
Top-of-the-line GNSS receiver able to make ► *carrier phase* and ► *pseudorange* measurements on multiple L-band frequencies broadcast by several GNSS constellations.

Geodetic Reference System 1980 (GRS80)
The current internationally defined reference ellipsoid and associated gravitational field for geodetic applications.

Geographic Coordinates
A general name that refers to coordinates associated with the spherical shape of the Earth

Geographic Information System (GIS)
A software system that manages, analyses, displays spatial data that has been organized in *layers*. For the purpose of creating special feature maps, undertaking spatial analysis, assist in decision-making, and more. Sometimes the term may also refer to the spatial datasets themselves.

Geoid
A surface on which the Earth's gravity potential is a constant (equipotential or level surface) and that closely approximates global mean sea level.

Geoid Height
The ► *ellipsoidal height* of the ► *geoid*; also known as the geoid undulation.

Geoid Model
Representation of the ► *geoid height* across a local area, a region, or the globe. May be in the form of geoid height contours on the ► *reference ellipsoid*, as point values, or gridded data, or various mathematical functions – the most common being in the form of spherical harmonics.

Geoid Undulation
Same as ► *geoid height*.

Geostationary Earth Orbit (GEO)
A circular orbit at approximately 36 000 km altitude above the Earth's equator with an orbital period equal to the Earth's rotational period. A satellite in a geostationary Earth orbit will appear to be in a fixed position in the sky for terrestrial observers.

Geostationary Satellite
A satellite in a ► *geostationary Earth orbit*. Often used for communication and for ► *satellite-based augmentation systems*.

Global Navigation Satellite System (GNSS)
A navigation system that can provide a positioning solution anywhere in the world. The term is currently used collectively for GPS, Galileo, GLONASS, and BeiDou.

Global'naya Navigatsionnaya Sputnikova Sistema (GLONASS)
Global navigation satellite system of the Russian Federation, providing global permanent positioning, navigation and timing service for land, air and space users worldwide. GLONASS is a dual-use system providing both authorized and open access services.

Global Positioning System (GPS)
A global navigation satellite system owned and operated by the United States Air Force.

Gold Code
A family of ► *pseudo-random noise (PRN)* sequences with good auto and cross-correlation properties proposed by Robert Gold. Gold codes are, for example, employed for the GPS coarse and acquisition (► *C/A*) code.

GPS Aided GEO Augmented Navigation (GAGAN)
A ► *satellite-based augmentation system (SBAS)* developed by the Indian Space Research Organization, the Airports Authority of India, and the Directorate General of Civil Aviation to provide horizontal and vertical navigation throughout India. It has provided safety-of-life service since 2014.

GPS Time
The timescale used by GPS, which began at midnight ► *Universal Time Coordinated (UTC)* on January 5/6, 1980 and is not adjusted by leap seconds.

GPS Week
The integer number of weeks elapsed since the start of ► *GPS time*. GPS weeks start at midnight from Saturday (day-of-week 6) to Sunday (day-of-week 0). In accordance with the 10-bit representation of the GPS week in the legacy GPS ► *navigation message*, its value is often given modulo 1024, resulting in roll-overs in August 22, 1999 and April, 7 2019. RBL,OM)

Greenwich Mean Time (GMT)
A 24-hour time keeping system whose hours, minutes, and seconds represent the time-of-day at the Earth's prime meridian (0° longitude) located near Greenwich, England. GMT was adopted as the world's first global time standard in 1884. GMT no longer exists, since it was replaced by other astronomical time scales many years ago, which in turn were subsequently replaced by the atomic time scale UTC.

Greenwich Hour Angle
The angle at a specified epoch between the x-axes of the ► *Earth-centered inertial* and ► *coordinate systems*.

Grid Ionospheric Vertical Error (GIVE)
A parameter broadcast by SBAS to indicate the possible magnitude of the vertical delay error for a specific ionospheric grid point delay estimate. GIVE is determined from a broadcast 4-bit number, called the GIVE indicator or GIVEI. A look up table is used to convert the indicator to a 1-sigma overbound value (► *overbound*) called the σ_{GIVE}. By tradition, GIVE itself is a 99.9% number or $3.29 \times \sigma_{\mathrm{GIVE}}$. A relevant set of σGIVEs is used to interpolate the corresponding User Ionospheric Vertical Error overbound, σ_{UIVE}. This vertical overbound is finally multiplied by the obliquity factor to obtain the complete User Ionospheric Range Error overbound, σ_{UIRE}.

Ground-based Augmentation System (GBAS)
A local area differential GNSS augmentation system using multiple airport-based reference receivers that provide corrections and integrity information to users via a very-high frequency (VHF) data link known as the ► *VHF data broadcast (VDB)*. GBAS supports aircraft performing precision approach and landing operations as well as other operations near GBAS-equipped airports.

Ground Plane
An electrically conducting flat surface at the *bottom* of an ► *antenna* that reflects electromagnetic waves. Optimum antenna properties (such as ► *multipath resistance*) are obtained if the dimension of the ground plane is large compared to the ► *wavelength*.

Ground Segment
A major component of a ► *global navigation satellite system* providing satellite control and constellation keeping, as well as orbit and clock data calculation for mission operations.

Ground Station
A terrestrial radio station enabling communication with a satellite. Depending on the specific application, one may distinguish between various functions: telemetry stations for reception of satellite data on the ground, telecommand (or uplink) stations for sending control commends to the spacecraft, or tracking stations providing range, range rate or angular measurements for ► *orbit determination*.

Group Delay
is a measure of the propagation time of the amplitude envelope of an electromagnetic signal through a device or medium. In the context of GNSS, it describes the delay experienced by the code modulation upon signal propagation through a dispersive medium such as the ionosphere or parts of the signal generating, transmitting, or receiving equipment.

Group Velocity
Speed of propagation of the envelope, i. e., the code signal of navigation signals, of a modulated electromagnetic wave. It is a measure for the speed of movement of the wave energy.

H

Hand-Over Word (HOW)
The second 30-bit word within every GPS legacy navigation data 300-bit sub-frame. HOW includes a time stamp.

Harmonic
A signal whose frequency is an integer multiple of some other signal's frequency. Nonlinearity in any one of several stages involved in radio frequency transmission generates (typically undesired) power at harmonics of the transmission frequency.

Hatanaka Compression
A loss less technique used to compress GNSS data files in ► *Receiver Independent Exchange (RINEX)* format.

Helmert Transformation
A 7-parameter similarity transformation named after the geodesist and mathematician F. R. Helmert. It relates two frames through a shift vector, a rotation and a scale factor.

Higher-order Ionospheric (HOI) Terms
Contributions to the ionospheric delay of a GNSS signal, which depend on higher than second-order terms of the frequency and cannot by eliminated by the ► *ionosphere-free combinations* of two observations.

Horizon
The imaginary line of intersection between a plane tangent to the surface of the Earth at the observer and the celestial sphere. The horizon is the reference plane for the ► *horizontal system* with coordinates ► *azimuth* and ► *altitude*.

Horizontal System
A coordinate system related to the local horizon of an observer, and where the coordinates used are ► *azimuth* and ► *elevation*.

Hot Start
Activation of a GNSS receiver with prior information on the approximate time and user position as well as

the broadcast ephemeris of the GNSS satellites to speed up the signal search and acquisition and to enable an immediate computation of the navigation solution after collection of valid ► *pseudorange* measurements.

Hour Angle
Difference between the local ► *sidereal time* and the ► *right ascension* of a star. The hour angle measures the sidereal time that has passed since the last culmination.

Hydrogen Maser
A signal generator based on the hyperfine transition of the neutral hydrogen atom at 1420.405752 MHz.

Hydrographic Surveying
A form of surveying in support of offshore engineering (such as associated with pipelines, undersea cables, breakwaters, harbor works, dredging, etc.) and sea floor charting.

Hydrostatic Delay
The dry component of the ► *slant total delay*.

Hypothesis Testing
is a formalized decision rule of rejecting or not rejecting the null hypothesis. The null hypothesis, representing the model one believes to be true, is thereby compared to one or more alternative hypotheses.

I

IF-level Simulator
A simulator that generates intermediate frequency (IF) samples of GNSS signals similar to those expected at the output of the receivers' front end. These samples can be processed directly by the digital processor of a receiver, or, with a digital-to-analog converter and an up-converter, can be converted to RF signals for conductive or rebroadcast testing.

Inclined Geosynchronous Orbit (IGSO)
An orbit synchronous with the Earth'S rotation period of about 24 h but inclined with respect to the Earth's equator. IGSO satellites are commonly used for regional navigation satellite systems as a complement to strictly ► *geostationary satellites*.

Inertial Measurement Unit
An electronic measurement device combining accelerometers and gyros to measure the specific force and angular rate of the body to which the sensor is attached.

Inertial System/Frame
A non-rotating system or frame in free fall with respect to the ambient gravitational field. *Pseudo* or *quasi* are sometimes appended to distinguish it from the original Newtonian concept of a frame at rest or having only constant rectilinear motion.

Influential Bias
A ► *bias* that propagates into the parameter estimator; such bias lies in the range space of the design matrix. A non-testable bias is always influential.

In-phase (I) Component
GNSS signals frequently use ► *quadrature phase shift keying* to transmit two orthogonal signal components. such as a civil and a military signal, on one frequency. In the case of GPS L5, the in-phase (I) component transmits the navigation data (► *data channel*), while the quadrature (Q) component (which is 90° out of phase) carries a dataless ► *pilot signal*.

Integer Ambiguity
The unknown number of wavelengths (cycles) that is contained in the measured carrier phase range from the receiver to satellite antenna.

Integer Ambiguity Resolution
The procedure by which the unknown double-differenced carrier-phase ambiguities are estimated and validated as integers. Once these ambiguities can be considered known, the corresponding carrier-phase measurements will act as very precise pseudorange measurements.

Integer Bootstrapping (IB)
Integer estimation that is based on a combination of ► *integer rounding* and sequential conditional least-squares estimation. The success rate of integer bootstrapping is never smaller than that of integer rounding and never larger than that of ► *integer least-squares*.

Integer Least-squares (ILS)
Integer estimation that is based on the principle of least-squares. The ILS estimator has the largest success rate of all integer estimators. Its success rate is invariant for ► *Z-transformations*. In contrast to ► *integer rounding* and ► *integer bootstrapping*, the ILS-estimation requires an integer search.

Integer Rounding (IR)
Integer estimation that is based on scalar rounding to the nearest integer. The success rate of integer rounding is never larger than that of ► *integer bootstrapping* or ► *integer least-squares*.

Integrity
A measure of the trust that can be placed in the correctness of the position solution. Integrity includes the ability of a system to provide timely and valid warnings (alerts) to the user.

Inter-channel Bias (ICB)
Difference in code or phase biases of GLONASS ► *FDMA* signals transmitted on different frequency channels.

Interface Control Document (ICD)
A document describing the interfaces between the GNSS ► *space segment* and the ► *user segment*. It provides a description of the signal structure and modulation, the format and contents of the navigation data, as well as relevant algorithms for using these data in the positioning.

Interference
Radio frequency power in one or more GNSS bands that degrades a GNSS receiver's ability to acquire and track GNSS signals. Interference may be structured, as in GNSS ► *spoofing*, or unstructured, as in wideband Gaussian noise jamming. It may be intentional, as in deliberate jamming, or unintentional, as in noise generated by electronics surrounding a GNSS receiver.

Inter-frequency Bias (IFB)
Difference in code or phase hardware biases of signals with different frequencies.

Intermediate Frequency (IF)
A frequency lower than the carrier frequency to which the modulated GNSS signal is shifted to facilitate processing in the signal generation or processing chain.

International Atomic Time (TAI)
A time scale realized by a weighted average of the time kept by over 400 atomic clocks worldwide. It is the basis for ► *Coordinated Universal Time (UTC)*, which is used for civil timekeeping all over the Earth's surface. TAI is computed monthly by the International Bureau of Weights and Measurements (BIPM).

International Celestial Reference System (ICRS)
A system of coordinates and conventions that define coordinates of objects in inertial space. It is defined and maintained by the International Earth Rotation and Reference Systems Service (IERS).

International Celestial Reference Frame (ICRF)
A reference frame that realizes the ► *International Celestial Reference System* by means of coordinates of objects accessible directly by radio-astronomical observations.

International Terrestrial Reference System (ITRS)
A system of coordinates and conventions that define coordinates of points tied to the Earth. It is defined and maintained by the International Earth Rotation and Reference Systems Service (IERS).

International Terrestrial Reference Frame (ITRF)
A reference frame that realizes the ► *International Terrestrial Reference System* at a particular epoch by means of coordinates of definite points that are accessible directly by occupation or by observation. The IERS is responsible for computing the coordinates of this global network in order to realize the ITRF.

Interoperability
The ability of jointly using two independent navigation systems for with a resulting benefit over the use of each individual system. ► *Compatibility* of their signals is a prerequisite for the interoperability of two systems.

Interplex
A special case of a phase-shift-keyed/phase-modulated (PSK/PM) multichannel system that is characterized by high power efficiency for a number of components.

Inter-seismic
Between earthquakes. The inter-seismic period is the time period between major earthquakes on a given fault. In most models of the earthquake cycle, the rate of deformation is expected to be constant or varying only slowly for most of the inter-seismic period.

Inter-system Bias (ISB)
Difference in receiver hardware biases between signals of two GNSS constellations plus the offset between the time scales of the two systems.

Inter-satellite Type Bias (ISTB)
Difference in receiver hardware biases between signals transmitted by different satellite types within a constellation. In the case of BDS, the existence of inter-satellite type biases has been demonstrated for signals of geostationary satellites that are combined with those of other (IGSO, MEO) satellites.

Inter-Signal Correction (ISC)
Correction values in the GPS modernized navigation message to enable a consistent processing of different navigation signals using a single set of clock offset values. ISCs represent a specific form of ► *differential code biases*.

Ionosphere
The ionized part of the upper atmosphere from 50 km up to about 1000 km height. The ionospheric plasma is primarily produced by electromagnetic and particle radiation transmitted from the Sun. Consequently, the ionization level depends strongly on geographic location, season and local time. Spatial structure and dynamics of the ionospheric plasma are strongly coupled with other geospheres such as thermosphere and magnetosphere causing a high variability of the plasma density.

Ionosphere-free Combination
A linear combination of two GNSS observations, which eliminates the dominant contributions of ionospheric path delays that vary with the inverse square of the signal frequency.

Ionospheric Correction Models
In a first-order approach the ionospheric delay or range error is proportional to the ► *total electron content (TEC)* along the ray path. Therefore, to reduce ionospheric range errors in single frequency GNSS applications, ionospheric electron density models (► *NeQuick* for Galileo) or simple TEC models (e.g., ► *Klobuchar* model for GPS or NTCM) can be used.

Ionospheric Gradient
Steep variations in time and space of the ionosphere electron content, which cause large delays in the GNSS differential observations even for small baselines.

Ionospheric Grid Point (IGP)
A specific reference location on an imaginary thin shell above the Earth's surface. In ► *satellite-based augmentation systems (SBAS)* a set of IGPs is used to describe the ionosphere by transmitting ionospheric delay values for a fixed set of locations over the region of interest.

Ionospheric Perturbations
There exist several types of ► *space weather* driven temporal and spatial electron density perturbations in the ionosphere and plasma sphere that may impact GNSS in different ways. Besides radio ► *scintillations* caused by small scale electron density irregularities also medium scale and large scale ► *traveling ionospheric disturbances* (MSTIDs, LSTIDs) or solar flare induced sudden ionospheric disturbances (SIDs) may degrade the GNSS

performance in precision and safety of live applications.

Ionospheric Pierce Point (IPP)
A location, often specified by latitude and longitude, between the user and a satellite where the line of sight between the two intersects an imaginary thin shell above the Earth's surface, a shell in which all electrons are assumed to be concentrated. Most commonly the thin shell is specified to have a constant height of 350 km above the reference ► *ellipsoid* of the 1984 release of the ► *World Geodetic System (WGS-84)*

Ionospheric Refraction
The signal propagation delay and signal path bending induced by free electrons in the upper part of the atmosphere. Besides the plasma density along the ray path, ionospheric refraction depends on the radio wave frequency (dispersion) and the geomagnetic field vector along the ray path (anisotropy).

J

J2000
A standard epoch representing midday on January 1, 2000 (2000 Jan. 1.5 = JD 2451545.0).

Julian Day
A time unit of ► *dynamic time*. It is exactly 1/36525 of a Julian century.

Julian Day (JD) Number
An integer day number obtained by counting days from the starting point of noon on January 1, 4713 BC (Julian Day zero).

K

Kalman Filter
A recursive algorithm to obtain a ► *minimum mean squared error (MMSE) estimate* of the state vector of a linear dynamic system based on a time series of past and current observations. Each cycle of the recursion consists of a time-update and a measurement update. In the time-update the dynamic model is used to predict the state vector from the previous epoch, while in the measurement-update the measurements of the current epoch are used to improve upon the estimate of the predicted state vector.

Keplerian Elements
A set of six orbital elements used to describe the shape and spatial orientation of the orbit, typically comprising the semi-major axis, eccentricity, inclination, longitude of the ascending node, argument of perigee, and mean anomaly.

Keplerian Orbit
The trajectory of a satellite around a central point mass, for the special case of an attracting force proportional to the inverse square of the distance. Bound Keplerian orbits are ellipses confined to a fixed ► *orbital plane*.

Klobuchar Model
An empirical model used to describe the ionospheric time delay in single-frequency GNSS measurements. The Klobuchar ionospheric model was first adopted by the Global Positioning System but is also used by various other GNSSs in the same or slightly modified form. It comprises eight parameters that are broadcast by the GNSS satellites with at least daily updates.

Kinematic Positioning
Estimation of epoch-wise coordinates for a moving or non-moving GNSS receiver from observations covering a given data arc.

Korean Augmentation Satellite System (KASS)
A ► *satellite-based augmentation system (SBAS)* being developed by the Ministry of Land, Infrastructure, and Transport to provide horizontal and vertical navigation throughout the Korean peninsula.

L

Laser Time Transfer (LTT)
A technique for synchronization of space and ground clocks through the exchange of laser pulses. It combines ► *satellite laser ranging* with onboard measurements of the arrival time using a photo-detector on the satellite.

Latency
Delay in time after ► *differential GNSS* corrections are generated by the reference receiver or the network and the time they arrive and are applied by the user. Also: delay in the provision of precise orbit and clock products relative to the epoch of the GNSS observations used in their generation.

L-band
The band of the radio spectrum covering frequencies of 1–2 GHz.

Leap Second
An intentional time step of one second used to adjust ► *Universal Time Coordinated (UTC)* in order to ensure approximate agreement with UT1. An inserted second is called a positive leap second, and an omitted second is called a negative leap second.

Least-squares Ambiguity Decorrelation Adjustment (LAMBDA)
Method for the efficient computation of the integer least-squares ambiguity estimator. It makes use of a decorrelating ► *Z-transformation* to speed up the integer search and to compute an improved integer bootstrapping estimator as first approximation.

Least-squares Estimation
An estimation principle for solving an overdetermined system of equation by minimizing its (weighted) sum of squared residuals (the differences between input data and their estimated values).

Length-of-day
The rotational period of the solid Earth. The angular velocity of the solid Earth, and hence its period of

rotation, changes in response to the torques acting on it.

Light-time
The time that it takes an electromagnetic signal to pass the distance between the transmitter and receiver.

Linear Feedback Shift Registers (LFSR)
A shift register whose input binary state (0 or 1) is a linear function of its previous states. An *n*-stage shift register consists of *n* consecutive two-state stages (flip-flops) driven by a clock. At each pulse of the clock the state of each stage is shifted to the next stage in line to the right of the register. In order to convert the *n*-stage shift register into a sequence generator a feedback loop is incorporated, which calculates a new term for the left-most stage, based on the states of the *n* previous states. At the right-most stage of the register the generated sequence is output.

Line-of-sight (LOS)
Typically refers to the straight line between a GNSS satellite and the antenna of a GNSS receiver. The LOS signal is also referred to as the direct-path signal.

Line-of-sight Vector
Vector of unit length pointing from the receiver position to the satellite position.

Line Quality Factor
The ratio of the frequency of an atomic transition and the width of the resonance line. The ► *Allan Deviation* of an atomic clock is inversely proportional to the line quality factor, i. e., the clock stability improves with increasing quality factor.

Link budget
A budget of gains and losses in a telecommunication system. GNSS link budgets typically comprise the transmit power, the transmit and receive ► *antenna* gains, the ► *free-space loss* as well as atmospheric and cable losses.

Loading
The surface forces acting on the Earth from the movement of mass, and the deformation of the solid Earth in response to changing loading forces. Loading most commonly refers to water and atmospheric loading, but erosion and sedimentation can also produce measurable deformation where they are concentrated enough and involve a sufficiently large movement of mass.

Local Coordinates
Cartesian coordinates, often in a left-handed system, with the third axis along the local vertical.

Low Earth Orbit (LEO)
A satellite orbit with a representative altitude of about 300–1400 km that is commonly used for remote sensing missions.

Low-noise amplifier (LNA)
An electronic device to amplify electromagnetic signals, which is specifically designed to add only little noise and can thus be used for very weak signals.

M

Mapping Function
The ratio between the propagation delay through the atmosphere at a specified elevation angle and the propagation delay in the ► *zenith direction*.

Maser
A device producing coherent electromagnetic waves through *Microwave Amplification by Simulated Emission of Radiation (MASER)*. Hydrogen Masers are used as atomic clocks, characterized by a very good short-term stability.

Master-auxiliary Concept (MAC)
Method of providing ► *Network RTK* corrections to the rover, where absolute corrections from one of the reference stations of the network (i. e., the master) and differential corrections from other (auxiliary) reference stations are transmitted to the rover.

Master Clock
A precision clock that provides timing signals to synchronize slave clocks as part of a clock network.

Master Station
A processing facility that collects measurements from multiple ► *reference stations* and makes determinations on the performance of the GNSS satellites (and perhaps the ► *ionosphere*). A master station may calculate orbits, satellite clock states, differential corrections, confidence bounds, and/or integrity evaluations.

Matched Filter
A technique to reveal a weak signal of known structure by ► *correlation* with a replica.

Maximum Likelihood Estimator (MLE)
A parameter estimator of which the outcome maximizes the respective likelihood function.
A likelihood function is a parameter function that gives the probability or probability density for the occurrence of a corresponding observation or sample.

M-code
The modernized GPS military signals that are broadcast at center frequencies of 1575.42 MHz and 1227.6 MHz on Block IIR-M and subsequent GPS satellites.

Meaconing
A specialized spoofing attack in which an entire segment of radio frequency spectrum is captured and replayed. The term *meacon* is a portmanteau of *masking beacon*.

Mean Solar Time
An astronomical time scale that is based on the average length of the day, called the mean solar day. The length of an average day is different from a true or apparent solar day, due to daily variations, over the span of a year, in the Sun's apparent angular speed across the sky when viewed by an observer on Earth. Thus, the length of an average or mean solar day is used for a more uniform system of timekeeping.

Mean Tide System
A system (such as for coordinates) in which all

temporal tidal effects except the mean tidal effect have been removed.

Measurement-level Simulator
A simulator that generates pseudorange, carrier-phase, and/or Doppler measurements for computing the position and other relevant parameters in software. Typically used for testing the ability of a receiver or a third-party software to compute a correct solution.

Medium Altitude Earth Orbit (MEO)
An orbit with altitudes above ► *low Earth orbits* and below ► *geostationary orbits*. GNSS medium altitude Earth orbits are usually located at altitudes of about 20 000 km.

Meridian
An imaginary great circle on the celestial sphere that defines the plane that is parallel to the polar axis and contains a local vertical vector. The astronomic meridian plane contains the tangent to the local plumb line, and the geodetic meridian plane contain the local normal to the ellipsoid.

Minimal Detectable Bias (MDB)
The smallest bias that a test can detect for a given level of significance and ► *power*.

Minimum Descent Altitude or Height (MDA/H)
The lowest altitude or height to which a descent is authorized when an aircraft performs a ► *Non-precision Approach* procedure. Unlike a ► *Decision Altitude or Height* an aircraft must not descend below the MDA/H. The pilot may descend to this height and maintain it until reaching the missed approach point, where the missed approach must be initiated if the required visual references are not available.

Minimum Mean Penalty (MMP) Test
This ambiguity acceptance test penalizes certain ambiguity outcomes. The penalties (e.g., costs) are chosen by the user and can be made dependent on the application at hand. It is optimal in the sense that it minimizes the average of the assigned penalties.

Minimum Mean Square Error (MMSE) Estimator
The estimator that has the smallest mean-square-error of all estimators from a particular class. Often the class is restricted to the class of linear functions. The mean of the squared error is the mathematical expectation of the squared error.

Minimum Operating Performance Standards (MOPS)
A document describing the necessary requirements for an object to be awarded an airworthiness certificate. Federal advisory committees, operated by RTCA Inc., develop and document these requirements and the MOPS form the basis for Federal Aviation Administration (FAA) regulatory requirements.

Modified Julian Day Number
The ► *Julian day number* minus 2400000.5. The Modified Julian Date (MJD) has a starting point of midnight on November 17, 1858.

Modulation
The process of mapping ► *baseband* information to a high-frequency carrier for the purpose of transmission. This takes place by either varying amplitude, phase, or frequency of the carrier signal to be transmitted.

Monitoring Station
► *reference station*

Moore's Law
An empirical relation named after a founder of Intel Co., who observed that the number of transistors in integrated circuits was almost doubled every 2 years.

Multi-function Satellite Augmentation System (MSAS)
A ► *satellite-based augmentation system (SBAS)* developed by the Japanese Civil Aviation Bureau to provide horizontal navigation throughout the Japanese airspace. It has provided safety-of-life service since 2007.

Multipath
The phenomenon whereby a transmitted GNSS signal is received at the receiver via multiple paths due to reflection and diffraction in addition to the direct-path signal. The received superposition of direct and non-direct-path signals (also known as the non-line-of-sight signals) results in errors in the signal tracking.

Multipath-to-direct (M/D) Ratio
The amplitude of a multipath signal relative to the direct-path signal.

Multiplexed Binary Offset Carrier (MBOC) Modulation
A variant of the ► *BOC* modulation, in which two sub-carriers of different frequency and different amplitude are used concurrently (composite BOC or CBOC) or in which the two sub-carriers have equal amplitude but alternate times slots (► *time multiplexed BOC or TMBOC*). The addition of the high-frequency sub-carrier component aims at an improved multipath resistance without a notable increase of the spectral width.

Multivariate Constrained-least-squares Ambiguity Decorrelation Adjustment (MC-LAMBDA)
A method for the computation of the integer least-squares ambiguity estimator subject to nonlinear constraints, based on the ► *Least-squares Ambiguity Decorrelation Adjustment (LAMBDA)* method.

N

Nadir
The direction towards the center of the Earth, i. e., opposite to the ► *zenith*.

Notice Advisory to Navstar Users (NANU)
Notifications issued by the ► *Global Positioning System (GPS)* to alert users of non-nominal situations such as signal outages or special operations that may result in service interruptions. Similar notifications (NAGUs, NAQUs) are provided by ► *Galileo* and the ► *Quasi-Zenith Satellite System*.

Narrow-lane Observable
A linear combination of carrier-phase observations on two frequencies that is formed as the sum of the individual phase values expressed in cycles. It exhibits

a small effective wavelength, e.g., 10.7 cm for GPS L1 and L2.

Navigation
The estimation process for determining the system ► *pose* as it maneuvers. Also, the process of determining and implementing a trajectory for an autonomous system.

Navigation Message
The set of auxiliary parameters such as satellite orbit and clock information, ionospheric correction data, and time offset parameters, which are transmitted by a GNSS satellite to enable computation of a position fix from the ► *pseudorange* measurements.

Navigation Message Authentication
A GNSS signal authentication technique whereby unpredictable (to the public) but verifiable data are inserted into a GNSS signal's navigation data stream. The properties of unpredictability and verifiability can be achieved by means of a digital signature, which is generated by a secret (private) key but can be verified by a public key. Besides injecting verifiable randomness into the navigation data stream, the digital signature serves to authenticate all data in the stream as originating with the holder of the private key (e.g., the control segment for a particular GNSS constellation).

Navigation System Error (NSE)
The difference between the true position and the estimated position. This error is linked to the navigation system providing the position estimation.

NeQuick
An empirical model used to describe the ionospheric electron density. A specific version known as NeQuick-G has been adopted by the Galileo system. Here, the modeled electron density is integrated along the signal path and used to correct single-frequency code measurements. The NeQuick-G model parameters are broadcast by the Galileo satellites with at least a daily update interval.

Networked Transport of RTCM via Internet Protocol (NTRIP)
Protocol for the streaming of ► *differential GNSS* corrections in ► *RTCM* format via the Internet.

Network RTK (NRTK)
A ► *differential GNSS* positioning technique that extends the operational distance of the ► *real-time kinematic (RTK) positioning* technique from 10 km to about 100 km from the reference receiver. This is realized by employing a network of reference receivers that produces precise correction models of the distance-dependent biases (atmosphere, orbit).

Neuman-Hofman (NH) Code
A specific type of ► *secondary code* used in ► *pilot signals* of the modern GNSS navigation signals.

Noise
Random fluctuations in a measured signal.

Non-directional Beacon (NDB)
A radio beacon operating in the medium or low-frequency bandwidths used for aircraft navigation. NDBs transmit a signal of equal strength in all directions. ► *Automatic Direction Finding (ADF)* equipment on board aircraft uses bearings from NDBs for navigation purposes.

No-net-rotation
The conventional requirement that subsequent realizations of a reference system are parallel.

Non-precision Approach (NPA)
An aircraft approach procedure using lateral guidance to bring the aircraft to a point where the runway is in view and a visual landing can be performed. NPA procedures do not include vertical guidance and include a ► *Minimum Descent Altitude/Height*.

Notice to Airmen (NOTAM)
A notice containing information concerning the establishment, condition, or change in any aeronautical facility, service, procedure, or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.

Null Hypothesis
► *Hypothesis testing*

Numerically Controlled Oscillator (NCO)
A digital signal generator used to generate a harmonic wave of desired frequency, and, optionally, phase. It is used inside a ► *phase lock loop* or ► *frequency lock loop* to track the incoming carrier signal and to measure its phase and ► *Doppler shift*.

Nutation
An oscillation of the Earth's axis about its mean position, which is superimposed on precession and driven by the luni-solar gravitational torque. The nutation movement is the resultant of oscillations with different periods of which the more important is 18.6 years, corresponding to one rotation of the Moon's ascending node.

O

Obliquity
The angle between the equatorial and orbital planes of some body. For the Earth, the angle between the plane of the Earth's equator and the plane of the Earth's orbit about the Sun. The mean obliquity of the ecliptic is about 23.4°.

Obliquity Factor
The ratio between a slant path passing through a thin slab above the Earth to a vertical path passing through the same location in the slab. The obliquity factor (or ► *mapping function*) is used to convert a vertical ionospheric delay estimate into a slant delay estimate corresponding to the elevation angle of the path. For the thin shell model that assumes an ► *ionosphere* 350 km above the Earth, the obliquity factor ranges from 1 (for a satellite directly over head) to just over 3 (for a satellite close to the horizon).

Observation Session
The length of time a non-moving receiver makes sufficient observations (adequate change in satellite–receiver geometry) for reliable ► *static positioning*. It may be many hours in length for a long ► *baseline* and/or an ► *ambiguity float solution*, to as

short as a few seconds if the ambiguities have already been resolved.

Occultation
► *Radio Occultation*

Orbit
The trajectory of a natural or artificial satellite around a central body – the Sun in the case of planets in the solar system, or the Earth in the case of artificial Earth-orbiting satellites.

Orbital Plane
The plane to which the motion of a satellite is confined in a central gravity field. In the presence of perturbations an ► *osculating* ► *orbit plane* is defined by the instantaneous position and velocity vector.

Orbit Determination
The process of estimating a set of parameters (including the initial position and velocity as well as various force mode parameters) describing the future motion of a satellite through a corresponding dynamical trajectory model.

Orbit Perturbations
Deviations of the orbital motion of a satellite around a central body from an idealized ► *Keplerian orbit*. Such perturbations are, e.g., caused by the aspherical gravity field of the Earth, the luni-solar gravitational attraction, atmospheric drag, and solar ► *radiation pressure*.

Oscillator
A device providing a periodical signal with a given frequency.

Outlier
A measurement that, relative to the assumed measurement noise probability distribution, is so rare that its validity is questionable.

Overbound
A probability distribution whose likelihood of having an error magnitude greater than some value is at least as large as the likelihood that the true error magnitude is greater than that value. The overbound is most commonly specified as a 1-sigma value for a zero-mean Gaussian distribution. The overbound is used to conservatively describe a true error distribution.

Overall Model Test
A test that tests the null hypothesis (► *hypothesis testing*) against the most relaxed alternative. This test is used for detecting unspecified modeling errors in the null hypothesis.

Overlay Code
► *Secondary code*

P

Parametry Zemli 1990 (PZ-90)
An Earth model maintained by the Military Topography Agency of the General Staff of the Armed Forces of the Russian Federation. The definition of PZ-90 comprises fundamental geodetic constants, parameters of the Earth's ellipsoid, and the Earth's gravity field parameters, as well as the geocentric reference system, which is defined in accordance with common conventions of the International Earth Rotation and Reference Systems Service (IERS) and Bureau International de l'Heure (BIH). PZ-90 serves as the ► *datum* for ► *GLONASS* ► *single-point positioning*.

Partial Ambiguity Resolution (PAR)
Ambiguity resolution when only a part of the ambiguities are resolved as integers. PAR can be applied in case the GNSS model is not strong enough to enable successful ambiguity resolution of all ambiguities. PAR is usually applied after the ambiguities have been re-parameterized with a proper ► *Z-transformation*.

Parts-per-million (ppm)
A relative accuracy measure defined as the ratio of accuracy to ► *baseline* length scaled by one million. For example, 1 ppm is 1 cm accuracy between two GNSS receivers separated by 10 km, or 10 cm over 100 km, etc. Parts-per-billion (ppb) is obtained as ppm $\times$ 1000. For example, 10 ppb is 1 cm accuracy between two GNSS receivers separated by 1000 km.

P-code
The precision (P) ranging code modulated onto both L1 and L2 carriers in GPS and GLONASS. The GPS P-code is referred to as the Y-code if it is encrypted. In the case of GPS, only authorized receivers are capable of directly tracking the Y-code. Civilian receivers use ► *semi-codeless tracking* techniques to obtain P(Y)-code pseudorange measurements.

Performance-based Navigation (PBN)
► *Area navigation* based on performance requirements for aircraft operating along an air traffic service route, on an instrument approach procedure or in a designated airspace. Airborne performance requirements are expressed in navigation specifications in terms of ► *accuracy*, ► *integrity*, ► *continuity*, and functionality needed for the proposed operation in the context of a particular airspace concept. Within the airspace concept, the availability of GNSS signal-in-space (SIS) or that of some other applicable navigation infrastructure has to be considered in order to enable the navigation application.

Perifocal Coordinates
Position of a celestial body relative to its orbital plane and the line of apsides.

Perigee
The closest point of an artificial satellite's orbit around the Earth.

Phase Bias
The signal hardware delay at receiver and transmitter side associated with the carrier phase signal generation.

Phase Center Offset (PCO)
The separation vector between the ► *antenna reference point* and the ► *antenna phase center*.

Phase Center Variation
Deviations of the antenna radiation pattern from a perfect sphere about the ► *antenna phase center*.

Phased-array Antenna
An array of antennas in which the relative phases of the signals coming to the antennas are combined in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions.

Phase-range Corrections
Corrections determined at a (network of) reference receiver(s) that are transmitted to a rover receiver in order to enable carrier-phase-based ► *differential GNSS* or ► *real-time kinematic positioning*.

Phase Lock Loop (PLL)
A controller used to align the phase of a carrier replica inside a GNSS receiver with that of the incoming signal. It comprises a ► *numerically controlled oscillator*, a phase ► *discriminator* that senses the instantaneous tracking error, and a loop filter that provides a smoothed estimate of the phase error for feedback to the NCO.

Phase Unlock
Failure to maintain phase tracking lock in a carrier phase tracking loop, resulting in a single ► *cycle slip* or a succession of cycle slips.

Phase Velocity
The speed of propagation of the carrier signal of an electromagnetic wave at a single frequency. It describes the velocity of movement of the phase front.

Phase Wind-up
The change in the received signal phase due to rotational changes in the relative orientation between receiver and transmitter antenna in the direction of signal propagation.

Pilot Signal
A GNSS signal component that does not contain data and is only modulated with a ranging code. Pilot signals allow for extended integration times for improved tracking sensitivity and robustness. Often, a ► *tiered code* is used for pilot signals in which a medium length primary ranging code is combined with a short ► *secondary code*.

Pivot Receiver/Satellite
Receiver or satellite that is selected as reference for forming ► *between-receiver* or ► *between-satellite differences*, respectively.

Plate Boundary Zone
The boundaries between tectonic plates are observed to be diffuse and often involve deformation spread out over regions hundreds to even 1000 km wide. Within a plate boundary zone, several active faults may take up the relative plate motion between the major plates, sometimes with large undeforming regions inside the plate boundary zone.

Plate Motion
The surface of the Earth is broken up into a set of tectonic plates, which are rigid except near their edges and which are all moving relative to each other. Plate motions are steady with time, changing only over long timescales, like hundreds of thousands of years. Plate motions are described in terms of rotations on the surface of a sphere about a geocentric axis.

Polarization
The direction of the oscillation of the electromagnetic field as a function of time. GNSS signals are circularly polarized, i. e., the field vector rotates along the propagation direction.

Polar Motion
The motion of the ► *celestial intermediate pole* with respect to the crust and mantle of the Earth. Can also refer to the motion of some other pole, such as the rotation pole, with respect to the crust and mantle of the Earth.

Pose
The position and attitude of an entity.

Positioning
Determination of the position coordinates of a location (in a reference frame) by means of measurement techniques in which the instrument is either placed on the position to be determined, or where the instrument measures the location of which the position has to be determined.

Position Dilution of Precision (PDOP)
► *Dilution of Precision*

Postseismic
Immediately after an earthquake. Transient deformation processes are observed to occur immediately after large earthquakes. These processes may cause very rapid deformation for a short time after the earthquake, and the rate of deformation decays with time back to a background, interseismic rate.

Power (statistical)
One minus the ► *probability of missed detection*.

Preamble
A well-defined bit sequence used to identify the start of data frames in the GNSS navigation message.

Precession
The slow variations in the directions of the Earth's instantaneous spin axis and of the ► *vernal equinox* relative to the celestial sphere due to the gravitational actions of the Sun, Moon, and planets on the Earth's orbit and its non-spherical shape and non-homogeneous constitution.

Precise Orbit Determination (POD)
A technique that combines methods and strategies to derive precise (typically of sub-decimeter accuracy) satellite positions using either a dynamic (relying on accurate modeling of forces acting on a satellite) or kinematic (trajectory through epoch-wide representation) approach.

Precise Point Positioning (PPP)
A technique that makes use of pseudorange and carrier phase observations of only a single receiver along with precise orbit and clock information of the GNSS satellites for determining the position of the receiver antenna.

Precise Point Positioning Real-time Kinematic (PPP-RTK)
Extension of the ► *precise point positioning (PPP)* technique by including satellite phase bias corrections such that the single-station carrier-phase ambiguities can be resolved to integers and, consequently, the PPP precision can be improved to centimeter level.

Precise Positioning Service (PPS)
One of two services provided by GPS that is intended for authorized (e.g., military) users only and based upon the ► *P(Y)-code* signals on two frequencies, GPS L1 and L2.

Precision
A measure for the reproducibility of measured or estimated quantity when measurement or estimation is repeated under similar circumstances.

Precision Approach
an instrument approach procedure using precise lateral and vertical guidance flown to a ► *decision altitude/height*.

Prediction (statistical)
Estimation of the outcome or realization of a random variable or vector. An observable random vector is used to guess the outcome of another non-observed random vector.The non-observable vector may comprise model parameters to be predicted in time or in space, but also signal and/or noise parameters.

Probability of False Alarm
The chance of rejecting the null hypothesis (► *hypothesis testing*) while it is true. It is also known as the significance level and it is usually denoted by α.

Probability of Hazardous Missed Detection
The product of the ► *probability of hazardous occurrence* and ► *probability of missed detection*

Probability of Hazardous Occurrence
Probability of having the outcome of the GNSS parameter estimator lie outside a pre-defined, non-hazardous parameter region. This probability increases as the influential ► *bias-to-noise ratio* gets larger.

Probability of Missed Detection
The chance of not rejecting the null hypothesis (► *hypothesis testing*) while it is false. It is usually denoted by β. This probability gets smaller as the testable ► *bias-to-noise ratio* gets larger.

Proper Time
The time scale associated with an observer at rest in a local frame.

Protection Level
The maximum possible positioning error that may be present for a navigation system at the current time, for a specified probability level. Usually, the protection level is compared to a corresponding ► *alert limit* to determine whether the navigation system meets the operational requirements at that time.

PRN Number
A number used to identify a GPS satellite based on the transmitted signal. More specifically, the PRN number denotes the serial number assigned to the ► *C/A-code* ► *pseudo-random noise sequence*.

Pseudolite
A device that transmits GNSS-like ranging signals from a known location to augment or replace the signals broadcast by GNSS satellites. The word is a contracted form of the composite term *pseudo-satellite*.

Pseudo-random (PR) Binary Sequence
► *Pseudo-random noise*

Pseudo-random Noise (PRN)
A quasi-random bit sequence of limited length with good cross and autocorrelation properties. PRN sequences are commonly used as ranging codes in GNSS systems.

Pseudorange
A distance-like measurement obtained from the time difference between transmission and reception of a radio signal and the known speed-of-light. Due to time offsets between the local clocks measuring the two times, the measurement differs from the true distance and includes a contribution related to these clock offsets. It is hence called a *pseudo*range.

Pseudorange Corrections
Corrections determined at a (network of) reference receiver(s) that are transmitted to a rover receiver in order to enable code-based ► *differential GNSS (DGNSS)* positioning.

Pull-in Region
Region in which every float ambiguity vector is pulled to the same integer vector. Pull-in regions are translational invariant regions that cover the ambiguity space without gaps and overlap. The shape of the pull-in region is defined by the type of integer estimator chosen.

P-value
A measure of strength-of-evidence on which the ► *hypothesis testing* decision to *reject* or *not reject* is made. Given the data, it is the smallest significance level at which the test rejects the null hypothesis.

P(Y)-code
A 10.23 MHz chipping rate, spread-spectrum signal broadcast by the GPS satellites on two frequencies, 1575.42 MHz and 1227.6 MHz. The precision (P)-code is unencrypted. For many years, the P-code has been encrypted into what is referred to as the ► *Y-code*. In common usage, P(Y)-code refers to the 10.23 MHz chipping rate GPS signals whether they are being broadcasted encrypted or unencrypted.

Q

Quadrature (Q) Component
A signal component transmitted with a 90° phase shift relative to the ► *in-phase component* of a compound navigation signal.

Quadrature Phase Shift Keying (QPSK)
A modulation scheme for radio navigation signals, in which two superimposed carriers with a 90° shift (known as in-phase and quadrature channel) are each modulated with a binary signal using ► *binary phase shift keying (BPSK)*.

Glossary

Quadrifilar Helix
A GNSS antenna made up of four wires arranged in a fractional-turn helix configuration and fed with progressive quadrature phase shifts.

Quantization
The process of converting a signal defined on a continuous range of values to one on a finite range of discrete values. The analog radio frequency signal received by a GNSS signal may be quantized to two, three, four, or more discrete quantization levels. Higher quantization resolution resulting from a larger number of quantization levels reduces signal distortion due to quantization.

Quartz Crystal Oscillator
A harmonic signal generator comprised of an specially cut quartz crystal device in a tuned circuit designed to produce a specific frequency signal. Design variations are employed to compensate for environmental effects on the crystal device that may cause frequency changes.

Quasi-Zenith Satellite System (QZSS)
A regional Japanese navigation system, which uses slightly eccentric ► *inclined geosynchronous orbits* to ensure that at least one satellite is always visible at high elevations for users in the service area.

Quaternion
A real-valued, four-component entity that extends the space of complex numbers by defining a hypercomplex mathematical object. A subset of the space of quaternions (quaternion with unit norm) can be used to parameterize a rotation.

R

Radiation Pressure
The pressure caused by the absorption or reflection of photons impinging on the surface of a satellite. For GNSS satellites with large solar panels, radiation pressure is a dominant source of ► *orbital perturbations*. Aside from the direct solar radiation pressure, reflected solar radiation of the Earth (► *albedo*) or the Earth's infrared radiation contribute to the total acceleration.

Radio-determination Satellite Service (RDSS)
A service defined by the International Telecommunications Union (ITU) for location determination and reporting of mobile users using radio signals in the L-band (uplink) and S-band (downlink).

Radio Occultation
A radio technique that measures the change of radio wave parameters such as signal strength and phase at grazing incidence when the radio wave continuously approaches the surface of a planet until the radio wave finally disappears. The technique has been widely used to explore planetary atmospheres such as Venus and Mars. The GNSS radio occultation technique uses the changing refraction of GNSS signals while approaching the Earth's atmosphere to retrieve vertical profiles of the electron and neutral gas densities of the ionosphere and troposphere, respectively.

Radome
A dome that covers, e.g., a ► *choke-ring antenna*, as typically used for geodetic surveying applications or at a ► *reference station*.

Ranging Code
A binary sequence modulated on a carrier wave to enable ► *(pseudo)range* measurements. GNSS uses ► *pseudo-random noise (PRN)* sequences as ranging code.

Ratio Test
An ambiguity test to decide whether or not to accept the estimated ► *integer ambiguity vector*. The test is based on the ratio of two quadratic forms, measuring the closeness of the float ambiguity vector to the estimated integer vector and the next nearest integer vector.

Ray Tracing
The reconstruction of the signal path through different media.

Real-time Kinematic (RTK) Positioning
► *Differential GNSS* positioning technique that is driven by carrier-phase data based on a baseline set up between a reference and rover receiver. Essential to high-precision RTK positioning is carrier-phase integer ambiguity resolution. Code (pseudorange) data are used in addition to the phase data to strengthen the RTK positioning model. For sufficiently short baselines (e.g., less than 10 km) the differential atmospheric biases can be neglected and very fast integer ambiguity resolution is feasible.

Rebroadcast Test
Testing a receiver by broadcasting GNSS signals (usually simulated) toward the device under test from one or more transmitter positions. Typically conducted when the antenna is integrated into the device under test, or when it is necessary to include the antenna in the test chain.

Receiver Autonomous Integrity Monitoring (RAIM)
A testing procedure whereby the redundant observations available at the GNSS receiver are autonomously processed to monitor the integrity of the GNSS signals with the purpose of providing relevant warnings.

Receiver Independent Exchange Format (RINEX)
The receiver independet exchange format is an ASCII-based format for GNSS observation and navigation data, as well as meteorological data.

Record-and-playback System
A system capable of recording received GNSS signals as intermediate frequency samples and, at a later time, up-converting the replayed signals for input to a GNSS receiver.

Redundancy
The total number of available observations minus the number of observations that are strictly needed to solve the system of equations. For a linear system of

observation equations it equals the difference between the number of observations and the rank of the system matrix.

Reference Ellipsoid
That ► *ellipsoid* adopted for a particular national or global ► *datum* or ► *reference frame*, such as the ITRF. The ► *Geodetic Reference System 1980 (GRS80)* ellipsoid is an internationally recognized reference ellipsoid.

Reference Frame
The realization of a ► *reference system* by means of coordinates of ► *control points* or ground marks that are accessible directly by occupation or by observation; for example, the ► *International Terrestrial Reference Frame (ITRF)*.

Reference Station
A GNSS receiver at a precisely surveyed antenna location (i. e., with known coordinates expressed in a ► *reference frame*), whose measurements are used to monitor, and possibly correct, any observable satellite signal errors. The reference station can act as the coordinate fixed point for baseline solutions or relative positioning determination with GNSS techniques such as ► *differential positioning (DGNSS)* or ► *real-time kinematic (RTK)* positioning.

Reference System
A set of prescriptions and conventions together with the modeling required to define at any time a triad of Cartesian coordinate axes.

Reflectometry
Method to establish properties of a reflecting surface by comparing the properties of incident (or a replica) and reflected electromagnetic signals.

Refraction
The deflection of GNSS signals in the Earth's atmosphere.

Regional Argumentation
The provision of additional parameters derived from regional GNSS observations to support ► *Precise Point Positioning (PPP)*

Relative Positioning
► *Differential GNSS*

Required Navigation Performance (RNP)
A form of ► *Area Navigation (RNAV)* with the addition of an on-board performance monitoring and alerting capability.

RF-level Simulation
A simulator that generates radio-frequency (RF) signals similar to those expected at the input of an antenna. Typically used for conductive testing, but rebroadcast testing is also possible.

Right Ascension
The longitude in a ► *celestial coordinate* system. Right ascension is the angle between the reference direction (at or close to the ► *vernal equinox*) and the projection of a bodies position on the equatorial plane, measured in an eastern direction.

RINEX
► *Receiver independent exchange format*

Rodrigues Vector
A vector of ► *attitude parameters* derived from the elements of a ► *quaternion*.

Rotation Poles
The two points, the north rotation pole and the south rotation pole, defined by the intersection of the Earth's rotation axis with the surface of the Earth.

RTCM Message Format
Standardized format for the exchange of GNSS observations, ephemerides, and correction data as defined and published by the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM SC-104).

Rubidium Atomic Frequency Standard
A signal generator that produces a stable signal based on optically pumping the hyperfine frequency of Rubidium 87 at 6.834682611 GHz, where the Rubidium is suspended in a gas cell.

S

S-band
A part of the spectrum of electromagnetic waves with carrier frequencies in the range of 2–4 GHz.

Sagnac Correction
In the context of GNSS, the Sagnac or Earth-rotation correction denotes a (non-relativistic) correction of the satellite positions that must be applied in the computation of the navigation solution when working in a rotating, Earth-fixed reference frame, to properly account for the Earth's rotation during the signal propagation time.

Sample Rate
The frequency at which a signal is measured.

Satellite-based Augmentation System (SBAS)
A wide area differential GNSS augmentation system using a regional monitoring network to collect data from core constellations and providing a navigation message to users via satellites in ► *geostationary orbit*. Examples include the US ► *Wide Area Augmentation System (WAAS)*, the ► *European Geostationary Navigation Overlay Service (EGNOS)*, the Japanese ► *Multi-function Satellite Augmentation System (MSAS)*, and the Indian ► *GPS Aided GEO Augmented Navigation (GAGAN)* system.

Satellite Laser Ranging (SLR)
A geodetic technique that provides distance measurements between satellites and a ground station based on the signal turn-around time of laser pulses.

Scintillation
Temporal fluctuations in phase and intensity caused by electron density irregularities along a transionospheric signal's propagation path. Scintillation effects may lead to severe signal fading (e.g., deep power fades $>$ 15 dB) associated with loss of lock and extremely enhanced phase noise.

Search and Rescue (SAR)
A secondary mission for some GNSS constellations, which involves the detection of internationally standardized distress signals from emergency beacons

and relaying of this information to government authorities.

Second
The duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom. The definition was added to the International System (SI) of units in 1967.

Secondary Code
A short binary pattern that is applied to subsequent repetitions of a fast, medium-length, primary spreading code to form a long ► *tiered code* that enables long integration times. Also referred to as an overlay or synchronization code.

Selective Availability (SA)
An intentional degradation of the clock phase to limit the accuracy of the ► *standard positioning service* of the ► *Global Positioning System (GPS)* for civil users to approximately 150 m. Selective availability was finally abandoned by presidential order in May 2000.

Semi-codeless Tracking
A special technique to track the encrypted ► *Y-code* signal of the GPS satellites without full knowledge of the signal. It is based on the assumption that the Y-code results from the known ► *P-code* by multiplication with an unknown low rate ($\approx$ 500 kHz) *W-code*.

Semi-kinematic Positioning
► *Differential GNSS* positioning technique in which carrier-phase (and pseudorange) data are collected for a rover receiver that is moving with respect to a stationary reference receiver. The rover receiver collects data during a short time (a few minutes) and then moves to the next point, continuously tracking the signals. To avoid a long observation time span during which the rover cannot move (as with conventional static positioning), special measurement procedures have been developed (i. e., revisiting of stations, starting from a known baseline, with antenna swap).

Semi-major Axis
Half the *large diameter* of an ellipse, i. e., the radius of an encompassing circle. For an elliptic satellite orbit, the semi-major axis denotes the mean value of the minimum and maximum orbital distance from the central body.

Shapiro Effect
The gravitational time delay experienced by an electromagnetic signal due to the presence of a massive body close to the signal transmission path.

Shielding Chamber
A chamber or cabinet designed to contain radio-frequency signals. Typically used for broadcast testing of radio-frequency equipment when the device under test must be shielded from external signals and/or when the broadcast signals are in a protected or restricted band.

Sidereal Day
The interval of time between two consecutive upper transits of the ► *vernal equinox* across some ► *meridian*. The mean sidereal day is 86 164.09054 s long and is a measure of the rotation of the Earth with respect to the stars.

Sidereal Time
The time associated with Earth's rotation relative to the celestial sphere, where 15° of rotation equals 1 h of sidereal time.

Signal-in-space Range Error (SISRE)
The user range error contributed by both the ► *space segment* and ► *ground segment*, but excluding ionosphere, troposphere, multipath errors, and receiver noise contributions. Usually applied to define the navigation service quality of the system itself.

Signal-to-noise Ratio (SNR)
A signal power to noise power ratio. It compares the level of a desired signal to the level of background noise.

Signal-to-interference-plus-noise ratio (SINR)
A signal power to noise-plus-interference power ratio.

Significance Level
The ► *probability of false alarm*.

SINEX
► *Solution independent exchange format*

Single-difference
► *Between-receiver difference* or ► *between-satellite difference* of GNSS observations and parameters.

Single Point Positioning (SPP)
An absolute GNSS positioning technique that is based on pseudorange measurements of at least four satellites with known positions and clocks offsets.

Slant Total Delay
The extra time needed for a signal propagating through the neutral atmosphere in a given (slant) direction compared to the propagation time in vacuum. It is often expressed in units of length, using the speed of light in vacuum for the conversion. For practical reasons, the slant total delay (STD) is divided into a slant hydrostatic delay (SHD) and a slant wet delay (SWD). A special case is the delay in the zenith direction. This zenith total delay (ZTD) is also divided into a zenith hydrostatic delay (ZHD) and a zenith wet delay (ZWD). The ZHD is approximately 2.3 m at sea level and proportional to the ground pressure. The ZWD can be anything between 0–40 cm, depending on the climate zone and the specific weather conditions.

Software Defined Radio (SDR)
A radio communication system implemented by means of software running on a processing system instead of typical implementation in hardware.

Solar Day
The interval of time between two consecutive transits of the Sun across some ► *meridian*. The nominal solar day is 86 400 s long and is a measure of the rotation of the Earth with respect to the Sun. The length of the solar day differs from that of the ► *sidereal day* by about 4 min because of the orbital motion of the Earth about the Sun.

Solar Radiation Pressure
The non-gravitational force acting on a satellite due to the direct radiation of the Sun (► *radiation pressure*).

Solar Radio Burst
An intense outburst of radio emissions from the Sun, with spectral power ranging from 3 MHz to above the L-band. A burst is typically associated with solar flares, which are caused by the acceleration of electrons in the solar atmosphere and whose rate of occurrence follows the 11-year sunspot cycle.

Solution Independent Exchange Format (SINEX)
An ASCII-based format for normal equation or variance/covariance matrices and related information. SINEX files computed by different analysis/combination centers are, e.g., the input for the computation of the ► *International Terrestrial Reference Frame*.

Space Segment
A key part of a ► *global navigation satellite system*, comprising the constellation of satellites with proper orbital geometry which transmits the navigation signals.

Space Vehicle Number (SVN)
A consecutive number assigned to different satellites of the Global Positioning System (GPS). Other than the pseudo-random noise (PRN) number the SVN is unique for a given spacecraft and does not change throughout its lifetime.

Space Weather
characterizes the energy, intensity, and composition of the electromagnetic and corpuscular solar radiation, galactic cosmic rays, and the associated state and coupling processes of the magnetosphere, ionosphere/plasmasphere, and thermosphere.

Specific Force
The non-gravitational force per unit of mass.

Spoofing
The act of generating a signal whose structure adheres closely enough to a GNSS signal specification that it can be misconstrued by a GNSS receiver as authentically broadcast by a GNSS satellite. Spoofing can be intentional, as in a deliberate attempt to manipulate the position, velocity, or time readout of a target GNSS receiver, or unintentional, as in an errant GNSS simulator or repeater signal that could be misinterpreted as originating from a GNSS satellite.

Standard Positioning Service (SPS)
One of two services provided by GPS that is intended for civilian use and is based upon the ► *C/A-code* signal on one frequency, GPS L1 (1575.42 MHz).

Static Positioning
Estimation of a single set of coordinates for a non-moving receiver from observations covering an extended observation data collection session (typically 1 or more hours). Referred to as rapid static positioning when the ► *observation session* is of the order of a few tens of minutes.

Stochastic Orbit Parameter
Empirical parameters such as accelerations or impulsive velocity increments that are introduced into the equation of motion of a satellite and adjusted in the orbit determination process to compensate for imperfections of the employed force model.

Stratosphere
is the layer in the Earth's atmosphere above the ► *troposphere*. It starts in about 8–13 km, but the actual value depends on the weather conditions and varies systematically with the latitude and the season. The top is at a height around 50 km.

Surface Acoustic Wave (SAW) Filter
A bandpass filter for radio frequency signals based on an electromechanical device that converts electrical signals to a mechanical wave and then back to electrical signals.

Surplus Satellite
An extra satellite in a GNSS constellation that is not operational (e.g., because it is older than its design life and suffers some performance degradation), but could be reactivated if needed.

System of Differential Correction and Monitoring (SDCM)
A ► *satellite-based augmentation system (SBAS)* being developed by the Russian Federation to provide horizontal and vertical navigation throughout Russia.

T

Terrestrial Time (TT)
Terrestrial Time is the relativistic timescale that replaced ► *Ephemeris Time (ET)* as the time reference for apparent geocentric ephemerides (► *Dynamical Time*). For practical purposes both time scales may be considered to be equivalent. Its origin is defined by the following relation to TAI: $\mathrm{TT} = \mathrm{TAI} + 32.184\,\mathrm{s}$ on January 1, 1977, 0 h TAI. TT is a theoretical ideal, which real clocks can only approximate; its best realization is TT(BIPM) provided on a yearly basis by the BIPM from a set of atomic clocks also used for TAI.

Testable Bias
Bias that propagates into the test statistic; such bias lies in the orthogonal complement of the design matrix range. A non-influential bias is always testable.

Test statistic
A function of the observables that is used to test hypotheses.

Thermal Noise
Broadband noise originating in an electrical conductor due to the random thermal motion of electrons. In a radio system such as a GNSS receiver, thermal noise originates primarily in the first amplifiers through which received signals pass. It can be accurately modeled as spectrally flat with an intensity proportional to temperature and having a Gaussian amplitude distribution.

Tides
Earth deformations induced by the luni-solar gravitational attraction and resulting in periodic ground motions (body tides) of several tens of centimeters, inducing periodic displacement of the liquids at the surface of the Earth (ocean tides).

Besides changing the position of points on the surface of the Earth, tides also cause small variations of the Earth's gravity field.

Tide-free System
A system (such as for coordinates) in which all tidal effects have been removed.

Tiered Code
A combination of a primary ranging code and a short ► *secondary code* commonly used in ► *pilot channels* of modern GNSS signals.

Time Division Multiple Access (TDMA)
A multiple access scheme, where channel users (satellites) occupy the complete available bandwidth but at different times, i. e., transmitting in turn in assigned time slots.

Time Multiplexed Binary Offset Carrier (TMBOC) Modulation
A modulation in which different ► *binary offset carrier modulations* pulse shapes are used for different chips of the pseudo-random binary sequence. For example, a mixture of BOC(1,1) and BOC(6,1) modulations is used for the ► *pilot component* of the GPS L1 civil (L1C) signal.

Time Scale
A continuous realization of a (conventional) reference frequency

Time-to-first-fix (TTFF)
The time between activation of a GNSS receiver and the first computation of a navigation solution. It is determined by the time required to search and for a sufficient number of satellites, to reliably track them and to decode the relevant parts of the navigation message. TTFF may vary from a few seconds for a ► *hot start*, to tens of seconds for a ► *warm start*, or even up to a few minutes for a receiver ► *cold start*.

Time-to-alert (TTA)
A maximum time allowed when a system that was previously declared safe for use can no longer assure that it meets all its integrity requirements for a given operation.

Time Transfer
The transfer of a precise reference time needed for remote synchronization. In scientific metrology, the time transfer is also used for remote comparisons of atomic clocks.

Timing Group Delay (TGD)
Scaled value of a satellite ► *differential code bias* as transmitted in the satellite's navigation message.

Tomography
Tomography refers to imaging of an object by penetrating waves whose modifications are measured after leaving the target. As an example, ground and space-based GNSS signals can be used to image the electron density distribution in the ionosphere and the water vapor distribution in the troposphere by measuring code and/or carrier phase changes.

Total Electron Content (TEC)
Integral of the electron density along a given ray path through the ionized atmosphere. Since each ray path has a specific geometry in concrete applications, TEC must be specified by both ends of the ray path and the elevation angle. In ground-based GNSS applications it is convenient for distinguishing between the slant TEC (STEC) along the entire ray path and the geometry free vertical TEC (VTEC) that describes the vertical electron content from the bottom of the ionosphere up to GNSS orbit heights and is commonly used as reference. TEC is usually measured in units of 10^{16} electrons per m^2 that is equivalent to 1 TEC unit (TECU).

Total Station
A survey instrument set up on a tripod over a ground mark that electronically measures the horizontal and vertical angles of the telescope when pointed at a target, as well as the distance to a reflecting prism (or reflective surface) using an infrared laser. Used to transfer geodetic coordinates from the ground mark to a target.

Tracking
The continuous alignment of a replica signal generated inside a GNSS receiver to the received signal. Based on the tracking process, which is initiated after the initial signal ► *acquisition*, measurements of code delay, carrier phase, and carrier can be obtained by the receiver.

Tracking Loop
A controller used to align a replica of the carrier or ranging code in a GNSS receiver with the incoming signal. A ► *phase lock loop (PLL)* or ► *frequency lock loop (FLL)* for carrier tracking is combined with a ► *delay lock loop (DLL)* to track the ranging signal.

Traveling Ionospheric Disturbance
Ionospheric perturbation of electron density characterized by a horizontal scale length of a few hundred kilometers that travel at velocities in the order of a few hundred meters per second. TIDs are often generated by ► *space weather* events, in particular at high latitudes due to the interaction of solar wind with the Earth's magnetosphere, causing enhanced ionization and heating. Here the enhanced solar energy input causes perturbation-related thermospheric winds and electromagnetic forces from the magnetosphere, which may move plasma perturbations, e.g., towards lower latitudes.

Traveling Wave Tube Amplifier (TWTA)
A traveling wave tube integrated with a regulated power supply and protection circuits used to produce high-power radio frequency signals.

Triple-difference
The time difference of ► *double-difference* GNSS observations.

Troposphere
is the lowest layer of the Earth's atmosphere, where the temperature on the average decreases with height. It ends at the tropopause, which is located in the range from 8 km to 13 km, depending on the weather conditions, and varies systematically with latitude and season. The troposphere contains the weather, e.g., clouds and precipitation.

Tropospheric Refraction
Describes the signal propagation delay and bending induced by the electromagnetic neutral part of the atmosphere (► *slant total delay*). The ► *wet delay* and ► *hydrostatic (dry) delay* components are typically separately modeled or accounted for in GNSS measurement processing.

Two-body Problem
The task of calculating the motion of two bodies under the influence of their mutual gravitational attraction. The two-body problem is a simplified representation of the motion of a satellite around the Earth, where all perturbations are neglected. The solution of the two-body problem is also termed a ► *Keplerian orbit*.

Two-way Satellite Time and Frequency Transfer (TWSTFT)
A high-precision long distance time and frequency transfer mechanism used for clock offset determination or time synchronization between two stations.

U

Uniformly Most Powerful Invariant (UMPI) Test Statistic
A test statistic that has uniformly the largest ► *power of all invariant statistics*

Universal Time (UT)
An irregular time scale based upon the rotation of the Earth. UT0 is a local time scale determined from observations taken at a single observing station. UT1 is UT0 corrected for the change in longitude of the observing station caused by polar motion. UT2 is UT1 corrected for seasonal variations. UT1 is proportional to the angle through which the Earth has rotated in space. The angular velocity of the Earth is proportional to the time rate-of-change of UT1.

Universal Time Coordinated (UTC)
Coordinated Universal Time is an atomic time aligned on the long-term on the Universal Time, i. e., the Earth's rotation. It is constructed by adding to the TAI, when needed, a leap second to keep the difference between UTC and UT less than 0.9 s. The difference between UTC and TAI is, therefore, always an integral number of seconds.

User Differential Range Error (UDRE)
A parameter broadcast by a ► *satellite-based augmentation system (SBAS)* to indicate the possible magnitude of the signal-in-space error for a specific satellite after applying the SBAS corrections. UDRE is determined from a broadcast 4-bit number, called the UDRE indicator or UDREI. A look up table is used to convert the indicator to a 1-sigma ► *overbound value* called the σ_{UDRE}. By tradition, UDRE itself is a 99.9% number or $3.29 \times \sigma_{\mathrm{UDRE}}$.

User Equipment Error (UEE)
Contributions to the pseudorange measurement and modeling errors that relate to the user equipment (such as multipath and receiver noise). Atmospheric errors such as residual tropospheric and ionospheric delays not taken into account by models or eliminated in a dual-frequency combination are also commonly attributed to the UEE.

User Equivalent Range Error (UERE)
The statistical error of the difference between observed and modeled pseudoranges that are used for computing a GNSS position solution. UERE is commonly split into contributions of the space and control segment (► *Signal-in-space Range Error, SISRE*) as well as contributions related to the user equipment and atmosphere (► *User Equipment Error, UEE*). Multiplication of UERE with the ► *dilution of precision* yields the statistical positioning error.

User Segment
The user equipment for tracking GNSS signals and for determining position, velocity, and time.

V

Vector Tracking Architecture
A GNSS signal tracking architecture in which the local code and carrier replica generators are driven not by single-channel local feedback, as in a traditional *scalar* tracking architecture, but by the state estimate of a consolidated position, velocity, and timing estimator that takes in data from all active channels. A vector architecture benefits from the mutual information in code phase, carrier phase, and Doppler measurements between channels and can thus provide more accurate and robust tracking than a scalar architecture.

Vernal Equinox
The point of intersection of the ► *ecliptic* and the ► *equator*, at which the Sun crosses the Equator from south to north, during its yearly passage along the ecliptic. This currently occurs on about March 21 each year. Historically, the vernal equinox served as origin of the measurement of ecliptic longitude as well as right ascension in the ► *celestial coordinate system*.

Very Long Baseline Interferometry (VLBI)
A space geodetic technique utilizing microwave signals from extragalactic radio sources (quasars). Basically, the signal travel time difference between two radio telescopes is measured. VLBI is the only technique to determine ► *Universal Time UT1* and ► *nutation* parameters, and is used to realize the ► *International Celestial Reference System*.

VHF Data Broadcast (VDB)
The transmission of ► *Ground-based Augmentation System (GBAS)* differential corrections and integrity information using the ILS localizer's VHF frequency band (108–118 MHz) and a time division multiple access (TDMA) data format defined in the GBAS ► *ICD*.

VHF Omnidirectional Range (VOR)
An aircraft navigation system operating in the very-high frequency (VHF) band. VORs broadcast a VHF radio composite signal that allows airborne receiving equipment to derive the magnetic bearing

from the station to the aircraft. This line of position is called a *radial*.

Virtual Clock
A technique used by ► *Chinese Area Positioning System* to implement satellite navigation. With the satellite virtual atomic clocks, the time at which the signals are transmitted from the ground can be delayed into the time that the signals are transmitted from the satellites, and the pseudorange measuring can be fulfilled as in GPS.

Virtual Reference Station (VRS) Approach
An approach that presents the data of a network of multiple reference stations to the user or rover as if coming from a single reference station, referred to as the virtual reference station.

Viterbi Decoder
A device or software for decoding a navigation message encoded with a convolutional code for ► *forward error correction*. It builds on algorithms for optimal decoding first published by A.J. Viterbi in 1967.

W

Wavelength
The spatial separation between consecutive maxima or minima of an electromagnetic wave at a given instant of time.

Walker Constellation
A specific arrangement of multiple satellites in circular orbits around the Earth that enables good coverage and visibility conditions. Following J. G. Walker, the constellation geometry is described by the total number of satellites, the number of orbital planes, and the along-track shift of corresponding satellites in neighboring planes. All satellites within a plane exhibit identical spacing and the same applies for the ► *ascending nodes* of the individual orbital planes.

Warm Start
Activation of a GNSS receiver with prior information on the approximate time and user position, as well as the coarse orbit of GNSS satellites to speed up the signal search and acquisition.

W-Code
A low rate code used to encrypt the ► *P-code* of the GPS L1 and L2 signal. The product of the W- and P-codes yields the so-called ► *Y-code*.

Wet Delay
The wet component of the ► *slant total delay*.

Wide Area Augmentation System (WAAS)
A ► *satellite-based augmentation system (SBAS)* developed by the US Federal Aviation Administration (FAA) to provide horizontal and vertical navigation throughout North America. It has provided safety-of-life service since 2003.

Wide-lane Observable
A linear combination of carrier-phase observations on two frequencies that exhibits a large effective wavelength. It is formed as the difference of the two carrier-phase observations expressed in cycles. For GPS L1 and L2 the wide-lane combination yields a wavelength of about 86 cm.

Wind-up
► *Phase wind-up*

World Geodetic System 1984 (WGS84)
A conventional terrestrial ► *reference frame* defined and maintained by the US Department of Defense. Nominally the ► *datum* for GPS ► *single point positioning*.

w-test Statistic
A ► *uniformly most powerful invariant (UMPI) test statistic* to test for the presence of one-dimensional biases. A special form of the w-test statistic is used in ► *data snooping* for the identification of observations contaminated with gross errors.

Y

Yaw-steering
The continuous control of a GNSS satellite's attitude around the Earth-pointing (yaw) axis to keep the solar panel axis perpendicular to the satellite–Sun direction.

Y-code
An encrypted version of the precise ranging code (P-code) transmitted by the GPS satellites on the L1 and L2 frequencies.

Z

Zenith
An imaginary point on the celestial sphere that is the projection of a local vertical direction. The astronomic zenith is the projection of the tangent to the local plumb line; the geodetic zenith is the projection of the local ellipsoid normal.

Zenith Total Delay
► *Slant Total Delay*

Zero-baseline
A setup of two or more GNSS receivers sharing a single antenna through a signal splitter.

Zero-tide System
A system specifically for the gravitational potential, in which all tidal effects except that of the permanent (mean) tidal deformation have been removed.

Z-tracking
An advanced technique for ► *semi-codeless tracking* of the GPS P(Y)-code on the L1 and L2 frequencies. The encryption signal bit is estimated separately in each frequency and fed to the other frequency to remove the encryption code from the signal. In this way, the code ranges and full wavelength L1 and L2 carrier phases are obtained. However, this method results in a signal-to-noise ratio degradation in comparison to the direct code correlation method.

Z-transformation
An integer preserving ambiguity transformation. A matrix is integer preserving if and only if all its

entries and those of its inverse are integer. Such transformations are used, e.g., in the ► *least-squares ambiguity decorrelation adjustment (LAMBDA)* method, to re-parameterize ambiguities so that they can be estimated with higher precision and less correlation.

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