ANTEX: the Antenna Exchange Format, Version 2.0

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Contents

1 Introduction

This document describes version 2.0 of the ANTenna EXchange (ANTEX) format of the International GNSS Service (IGS), which serves as the standard for IGS antenna models. Compared to previous versions, which were limited to antenna patterns for carrier phase modeling, the present release adds support for group delay and gain patterns. For improved efficiency, individual patterns can now be associated with multiple, constellation-specific frequency bands. As a major change, satellite transmit antenna data in the present format are now unambiguously referenced by the hardware-related space vehicle number (SVN) of the respective satellite, rather than the volatile pseudo-random noise (PRN) code or slot number, to improve transparency and to avoid undue redundancy. Time-dependent translations between the various satellite identifiers are made available through the IGS satellite metadata file, which complements the IGS antenna models and constitutes a necessary element for relating antenna data with satellite and signal codes in GNSS observation data.

Version 1 of the ANTEX format (Rothacher and Schmid, 2010) was developed at Technical University Munich (TUM) under the umbrella of the IGS to support a consistent modeling of antenna-related contributions in the orbit and clock determination as well as precise point positioning based on GPS/GLONASS observations. It covers both satellite transmit and ground receive antennas and provides information on the phase center offset as well as direction-dependent variations of the carrier phase range for individual GNSS frequency bands. Starting from relative calibrations, the IGS has essentially transitioned to absolute calibrations of receiver antennas obtained in anechoic chambers or robotic test facilities (Schmid et al, 2007) as a basis for the implementation of GNSS-based terrestrial reference frames (TRFs). GNSS transmit antenna patterns may include both inflight calibrations based on ionosphere-free dual-frequency observations as well as manufacturer calibrations with possible adjustments for TRF scale consistency.

Up to version 1.4, the ANTEX format was limited to information on the offset of the effective carrier phase center relative to an agreed upon mechanical reference point and associated carrier phase range variations relative to the phase center. For convenience, the carrier phase center was also considered as the reference for modeling pseudorange observations, even though the group delay variations may differ notably from those of the carrier phase and will thus result in different group delay phase centers. Furthermore, antenna gain characteristics are not covered by the legacy ANTEX format despite a growing need for link budget analyses in, e.g., spaceborne GNSS applications and GNSS reflectometry/scatterometry.

A practical issue, which causes an increased effort in the maintenance of IGS antenna models in ANTEX 1.x formats stems from the fact that satellite antenna patterns are traditionally referenced by the satellite's transmit identifier, i.e., the PRN code or slot number, which is also used to identify the transmitting satellite in GNSS observation data. While this facilitates the look up of antenna parameters for modeling a given observation it has so far required regular updates of the antenna model in case of PRN or slot number changes. With an increasing number of GNSSs and the deployment of ever new satellites new PRN assignments have become more frequent than desired and resulted in a substantial number of identical patterns for the same physical satellite under different transmit identifiers. Based on these considerations, a transition to a purely hardware-based reference as provided by the SVN appeared indispensable. In this way, unnecessary redundancy is avoid, but an additional step for translating between SVN- and PRN-based satellite references is required at the user end. The respective information is provided as part of the IGS satellite metadata file, which is continuously maintained by the IGS and contains a time-order list of transmit identifiers as used by each individual spacecraft and thus enables a seamless translation from SVNs to PRNs and vice versa at any given time.

Antenna parameters typically depend on the frequency of the transmitted/received signal, and are traditionally distinguished by a constellation-specific ANTEX frequency code related to the corresponding constellation and observation codes in other IGS data formats. Given the fact that different GNSSs may transmit signals on common center frequencies for interoperability, identical antenna parameters may apply for multiple constellations. While common-sense substitutions (e.g., GPS L1 patterns for Galileo E1 observations) have silently been assumed in the early processing of multi-GNSS data, explicit antenna data for all relevant constellation-specific frequency bands are nowadays provided for most receiver antennas, to avoid potentially erroneous substitutions. To avoid an excessive growth of antenna models due to incorporation of highly-redundant antenna data, dedicated substitution lists enabling a controlled use of individual data for multiple signals and/or frequencies have been added in this ANTEX version.

In terms of formatting, the ANTEX 2.0 format builds on the concepts and layout of the earlier 1.x versions. However, various new labels are used to accommodate the newly introduced or modified antenna parameters.

2 Antenna Parameters for GNSS Modeling

The ANTEX format provides a standardized interface for transmit and receive antenna parameters required in the analysis of GNSS pseudorange, carrier phase, and received signal power measurements (Rao et al, 2013). This section discusses the conceptual background for the description of application of these parameters in GNSS observation models.

2.1 Reference Frame

Individual antenna patterns and related properties are described with respect to an antenna reference frame (ARF), which is tied to the mechanical antenna structure. The ARF originates in the antenna reference point (ARP) and is defined by the principal axes of a right-handed Cartesian coordinate system. Here, the x- and y-axes span the mechanical antenna ground plane and the orthogonal z-axis points into the boresight direction of the antenna. Typically, a dedicated marker or structural element (e.g., the antenna cable connector) on the antenna is used to specify the exact location of the x- or y-axis with respect to the antenna body. For receiver antennas, a comprehensive set of ARF definitions with graphical illustrations is given in IGS (2025c). For clarity, the use of Up, East, North reference axes introduced in ANTEX 1.x for static reference sites is abandoned and it is emphasized that the ARF definition is fully independent of the orientation and possible motion of the antenna.

Irrespective of the specific antenna type and application, both the location of the ARP in a global reference frame and the orientation of the antenna axes, i.e., the transformation from the global reference frame to the mechanical ARF, must be known for modeling of GNSS observations and antenna-related range corrections. For stationary reference station antennas, the x-, y-, and z-antenna axis are nominally aligned with the East, North, and up directions, but possible angular offsets may need to be considered by the users for the transformation from the local horizontal system to the antenna frame in case of a non-perfect antenna orientation. For GNSS transmit antennas, all IGS models adopt an antenna frame that is rigorously aligned with the respective spacecraft body axes (Montenbruck et al, 2015). In case of manufacturer calibrations using different ARF definitions, the antenna data are transformed accordingly to comply with IGS conventions prior to publication in the IGS antenna model.

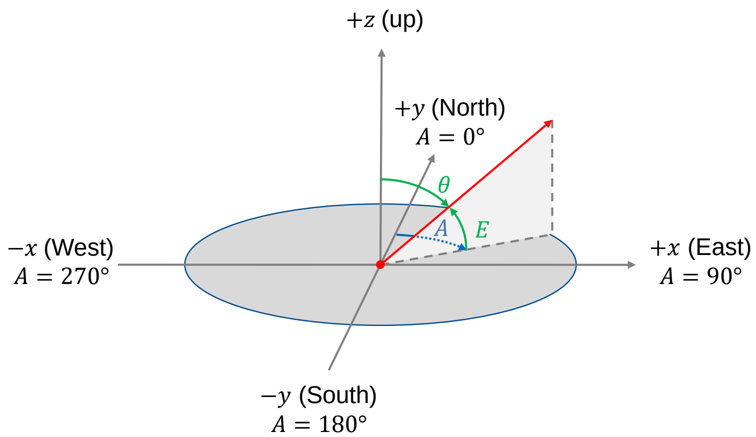

Fig. 1. Axes conventions and angles (off-boresight angle θ, azimuth A, and elevation E) for description of antenna parameters. North, East, and up indicate the nominal orientation of a stationary GNSS antenna in the local horizontal system and have formerly been used to designate the y-, x-, and z-axes in the ANTEX 1.x format.

Patterns are described on an equidistant, two-dimensional grid of off-boresight angles θ counted from the z-axis to the x/y-plane (antenna ground plane) and the azimuth angle A (Fig. 1). For best compatibility with legacy antenna models, the azimuth angle is counted in a clock-wise (left-handed) direction around the z-axis, from the $+y$-axis to the $+x$-axis of the antenna. Accordingly, the components of a line-of-sight unit vector $\boldsymbol{e}$ in the ARF are related to the angles (A, θ) used for the parameterization of antenna patterns in the ANTEX format by the relation

$$\boldsymbol{e} = \begin{pmatrix} e_x \\ e_y \\ e_z \end{pmatrix} = \begin{pmatrix} \sin(A)\sin(\theta) \\ \cos(A)\sin(\theta) \\ \cos(\theta) \end{pmatrix} \quad . \tag{1}$$

The use of a (left-handed) azimuth angle for GNSS antenna pattern specifications relates to the early use of GNSS for geodesy and has been retained as a standard for the IGS antenna models and the ANTEX format. For manufacturer calibrations of GNSS receiver and transmit antennas performed in anechoic chambers, the in-plane angle ϕ, counted in a mathematically positive sense from x to y, is most widely used. The two angles are related by $\phi = 90° - A$ which needs to be considered when transferring such calibrations into the ANTEX format. Furthermore, we may note that the off-boresight angle θ should be carefully distinguished from the "zenith angle" and the "nadir angle" that describe the relative Earth-receiver-satellite geometry. Both angles match the off-boresight angle only for a perfect zenith or nadir pointing, but deviations from the ideal situation are encountered in a variety of situations including land, ship, air and space navigation. As such, a clear conceptual distinction of the respective angles is encouraged in the description and handling of antenna models.

The ARP, i.e., the origin of the ARF, serves as the primary reference for modeling the geometric range between a pair of transmit (GNSS satellite) and receive (user equipment) antennas. The ARP of a receiving antenna is commonly defined geometrically in relation to the mechanical structure of the antenna. It generally coincides with the axis of attachment of the antenna to a monument or surveying instrument and may, for example be located at the bottom (BCR) or top (TCR) of chokering. Detailed specifications and graphical illustrations for commonly used geodetic and survey antennas are given in IGS (2025c). It also specifies the "north reference point (NRP)", i.e., the element of the antenna that defines the y-axis of the ARF and should be oriented toward the North direction for a static antenna.

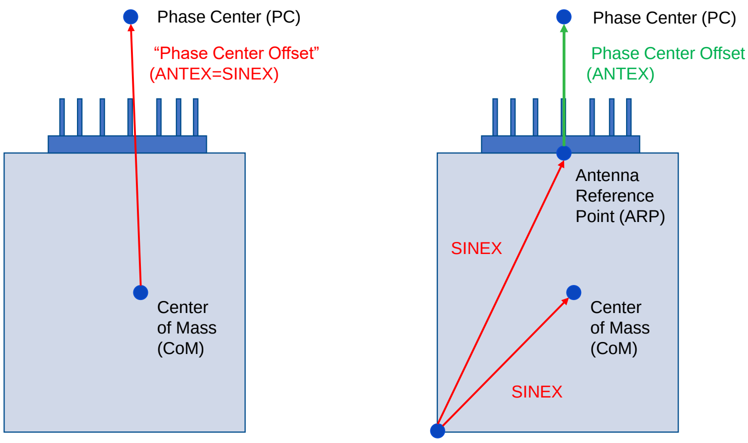

Fig. 2. Possible choices of the antenna reference point for a GNSS satellite antenna

Since information on the antenna assembly of GNSS satellites is only available to the public in rare cases, the spacecraft center of mass (CoM) has traditionally been adopted as ARP in all IGS antenna models so far. Since this may result in time varying phase center offsets due to fuel consumption over the satellite lifetime, use of an ARF tied to the spacecraft body frame is considered as an alternative for improved antenna models (Fig. 2). Making use of body-fixed ARP coordinates and (potentially time varying) CoM coordinates as provided in the IGS satellite metadata SINEX file (Steigenberger and Montenbruck, 2024), the antenna information can always be related to the CoM position as provided in the standard IGS orbit products. Within the ANTEX 2.0 format, the origin for code and phase center offsets of satellite transmit antennas is specified as part of the antenna record header.

2.2 Carrier Phase Range Corrections

The ANTEX antenna model provides line-of-sight-dependent corrections ζ to the carrier phase range related to a given satellite (transmit) or receiver antenna. Considering only the geometric range and the antenna-related contributions, the carrier phase range

$$\varphi = ||\boldsymbol{r}_{\text{sat,ARP}} - \boldsymbol{r}_{\text{rcv,ARP}}|| + \zeta_{\text{sat}}(\boldsymbol{e}_{\text{sat}}) + \zeta_{\text{rcv}}(\boldsymbol{e}_{\text{rcv}}) \tag{2}$$

is modeled as the sum of the geometric distance between the respective antenna reference points and the range corrections ζ associated with the individual antennas. By convention, the line-of-sight unit vectors $\boldsymbol{e}$ used to describe the direction-dependent phase patterns are always assumed to originate from the respective antenna and are thus given by

$$\boldsymbol{e}_{\text{rcv}} = \boldsymbol{A}_{\text{rcv}} \frac{\boldsymbol{r}_{\text{sat,ARP}} - \boldsymbol{r}_{\text{rcv,ARP}}}{||\boldsymbol{r}_{\text{sat,ARP}} - \boldsymbol{r}_{\text{rcv,ARP}}||} \quad \text{and} \quad \boldsymbol{e}_{\text{sat}} = -\boldsymbol{A}_{\text{sat}} \frac{\boldsymbol{r}_{\text{sat,ARP}} - \boldsymbol{r}_{\text{rcv,ARP}}}{||\boldsymbol{r}_{\text{sat,ARP}} - \boldsymbol{r}_{\text{rcv,ARP}}||} \; . \tag{3}$$

Here, the $\boldsymbol{A}$ denote the transformation between the global reference frame for describing the position of the satellite and receiver to the ARF of the respective antenna. Since carrier phase range corrections are frequency dependent, distinct corrections ζ_f are provided for the individual frequency bands f of relevance for GNSS signal processing. In practice, use of a mechanically-defined ARP for the description of antenna patterns may result in large variations of ζ across the antenna field of view. It is therefore common to partition the range correction for an individual antenna into two contributions, by introducing the concept of an antenna phase center (PC). The PC is considered to represent the radiometric center of the antenna, i.e., the approximate center of the near-spherical electro-magnetic wavefronts. The total range correction can then be expressed as

$$\zeta(\boldsymbol{e}) = -\boldsymbol{e}^T \Delta \boldsymbol{r}_{\text{PCO}} + \Delta\zeta(\boldsymbol{e}) \; , \tag{4}$$

where $\Delta \boldsymbol{r}_{\text{PCO}} = \boldsymbol{r}_{\text{PC}} - \boldsymbol{r}_{\text{ARP}}$ denotes the phase center offset (PCO) in relation to the ARP. The line-of-sight dependent phase variations relative to the corresponding phase center, i.e., the phase pattern, are described by $\Delta\zeta(\boldsymbol{e})$.

The PC itself can be determined in ground or inflight calibrations by minimizing the remaining phase pattern over a predefined range of boresight angles. It must be noted, though, that different weighting schemes, grid points, and cone angles in the minimization process may result in different PCs and the associated patterns. The overall phase correction $\zeta(\boldsymbol{e})$ remains unchanged when simultaneously replacing the PCO by

$$\Delta \boldsymbol{r}'_{\text{PCO}} = \Delta \boldsymbol{r}_{\text{PCO}} + \delta \boldsymbol{r}_{\text{PCO}} \tag{5}$$

and the associated pattern by

$$\Delta\zeta'(\boldsymbol{e}) = \Delta\zeta(\boldsymbol{e}) + \boldsymbol{e}^T \delta \boldsymbol{r}_{\text{PCO}} \; . \tag{6}$$

Considering, in particular the most common case of a PC shift along the boresight axis, i.e. $\delta \boldsymbol{r}_{\text{PCO}} = (0, 0, \delta z)$, the corresponding pattern is changed by $\delta z \cdot \cos\theta$. For completeness, we note that an alternative expression $-\delta z \cdot (1 - \cos\theta)$ is occasionally applied to the pattern for compensation of a PCO modification. In this way, the pattern remains unchanged, but an offset of δz is introduced in the carrier phase range. This offset is readily absorbed in carrier phase ambiguities or clock offsets, but can induce incompatibilities with fractional phase bias products used for integer ambiguity resolution in precise point positioning (PPP) applications.

Within the ANTEX format, antenna phase corrections are specified by the x, y, z components of the phase center offset $\Delta \boldsymbol{r}_{\text{PCO}}$ relative to the ARF as well as the associated phase variations $\Delta\zeta(Az, \theta)$ over an equidistant grid of azimuth and off-boresight angle values. In general, the carrier phase range correction depends on signal frequency. Therefore, multiple patterns can be specified for an individual antenna along with the corresponding GNSS frequency bands. Furthermore, time intervals of applicability may be assigned for individual patterns to cope with physical changes of the antenna characteristics observed over time on several GNSS satellites.

2.3 Code Range Corrections

Next to the carrier phase range, the non-uniformity of the antenna wavefront also affects the pseudorange measurements based on the modulated ranging code. Other than the mono-chromatic carrier, the modulated signal is based on a superposition of different frequencies. As a result, the group delay or code range variation caused by the antenna differs from the carrier phase range at the signal's center frequency. For sufficiently small chipping rates of the ranging code, the group delay variation (GDV) equals the derivative of the carrier phase range with respect to the frequency (Van Graas et al, 2004). It can thus be determined from phase pattern calibrations in an anechoic chamber over a set of frequencies next to the nominal GNSS frequencies. Alternatively, calibrations of relative code range changes in a robotic test facility (Kersten and Schön, 2017; Wübbena et al, 2019) or the analysis of code-minus-carrier observations (Wanninger et al, 2017; Beer et al, 2021) can be employed.

In analogy with the carrier phase range (Eq. 2), a basic pseudorange model including geometric distance and antenna-related, line-of-sight dependent code range corrections, is given by

$$p = ||\boldsymbol{r}_{\text{sat,ARP}} - \boldsymbol{r}_{\text{rcv,ARP}}|| + \xi_{\text{sat}}(\boldsymbol{e}_{\text{sat}}) + \xi_{\text{rcv}}(\boldsymbol{e}_{\text{rcv}}) \ . \tag{7}$$

Likewise, the total code range correction

$$\xi(\boldsymbol{e}) = -\boldsymbol{e}^T \Delta\boldsymbol{r}_{\text{CCO}} + \Delta\xi(\boldsymbol{e}) \tag{8}$$

can be partitioned into the contribution of a Code Center (CC) and its offset $\Delta\boldsymbol{r}_{\text{CCO}}$ from the ARF as well as the code pattern $\Delta\xi(\boldsymbol{e})$.

PPP standards currently employed within the IGS (Kouba et al, 2017) equate the CC to the PC and ignore the code pattern contribution. As a best practice, it is therefore recommended to align the CC and the code pattern obtained from an antenna calibration in such a way as to obtain matching Code Center Offsets (CCOs) and PCOs. This can readily be accomplished by considering that the total code range correction remains unchanged when simultaneously replacing the

$$\Delta\boldsymbol{r}'_{\text{CCO}} = \Delta\boldsymbol{r}_{\text{CCO}} + \delta\boldsymbol{r}_{\text{CCO}} \tag{9}$$

and the code pattern by

$$\Delta\xi'(\boldsymbol{e}) = \Delta\xi(\boldsymbol{e}) + \boldsymbol{e}^T \delta\boldsymbol{r}_{\text{CCO}} \ . \tag{10}$$

Within the ANTEX format, antenna calibrations for code range correction are specified by the x, y, z components of the code phase center offset $\Delta\boldsymbol{r}_{\text{CCO}}$ relative to the ARF as well as the associated pattern $\Delta\zeta(Az, \theta)$ over an equidistant grid of azimuth and off-boresight angle values. In general, the code range correction depends on the signal frequency. Therefore, multiple group delay patterns can be specified for an individual antenna along with the corresponding GNSS frequency bands. Furthermore, time intervals of applicability may be assigned for individual patterns.

2.4 Antenna Gain

Other than ideal point sources, radio antennas do not transmit electro-magnetic waves isotropically. For a given wavelength λ the directivity in the boresight direction increases with the antenna diameter. The variation of the transmitted radio flux with the antenna azimuth and off-boresight angle is described by the antenna gain $G(A, \theta)$, which is likewise a measure of the sensitivity for a receiving antenna. Overall, the electric power obtained at the output of a passive receiver antenna from a GNSS satellite transmitting the power P_{sat} via an antenna of gain G_{sat} is given by the relation

$$P_{\text{rcv}} = \frac{P_{\text{sat}} G_{\text{sat}} G_{\text{rcv}}}{L_{\text{rcv}}} \left(\frac{\lambda}{4\pi r} \right)^2 \tag{11}$$

where r is the satellite-receiver distance and L_{rcv} denotes any additional hardware losses that may arise in the conversion of electromagnetic waves into electric currents within the receiving antenna (Misra and Enge, 2011).

The tracking capability of a receiver and the achievable measurement noise are characterized by the carrier-to-noise density ratio C/N_0 of the signal power and the noise power N_0 in a 1 Hz bandwidth. The latter is commonly expressed as the product of the Boltzmann constant $k_{\text{B}} = 1.38 \times 10^{-23}\,\text{J/K}$ and the equivalent noise temperature T_{eq} that aggregates the contribution of individual noise sources in the antenna and receiver chain. Making use of the received power from Eq. (11), the resulting C/N_0 may be expressed in a logarithmic form as

$$\begin{aligned} (C/N_0)_{\text{[dBHz]}} \quad = \quad & P_{\text{sat,[dBW]}} + G(\boldsymbol{e}_{\text{sat}})_{\text{sat,[dB]}} + G(\boldsymbol{e}_{\text{rcv}})_{\text{rcv,[dB]}} \\ & -20 \log_{10}(4\pi r/\lambda) \\ & -10 \log(k_{\text{B}}) - T_{\text{eq,[dBK]}} - L_{\text{rcv,[dB]}} \ , \end{aligned} \tag{12}$$

with $10 \log(k_{\text{B}}) = -228.6$, which describes the impact of the transmit and receive antenna gain patterns on the tracking conditions as a function of the respective line-of-sight directions. It may be recognized that the link-budget described by Eq. (12) does not include the gain G_{LNA} of the low-noise amplifier (LNA) that is used to raise the power level of the received signals prior to entering the receiver. While the LNA gain affects the overall noise temperature, it does not add directly to the antenna gain, when computing the carrier-to-noise density ratio of the received signal. As such, gain pattern calibrations of active GNSS receiver antennas should be corrected for the respective LNA gain to provide only the gain of the passive antenna in the ANTEX file.

3 Format Description

The ANTEX 2.0 format inherits the basic concepts of its predecessors, but offers an extended set of data sections and labeled parameter lines to cover newly introduced and modified antenna parameters. The various formatting rules and options are specified in the present section along with illustrating examples.

3.1 General Conventions and Formatting Rules

The ANTEX format is based on text files using the 7-bit American Standard Code for Information Interchange (ASCII) encoding to support both human and machine reading. Depending on the specific operating system, a single line-feed (LF, `0x0A`; UNIX) character or a carriage-return/line-feed pair (CR LF, `0x0D` `0x0A`) is used to indicate the end of a text line. Users processing ANTEX files should be able to handle either representation or ensure prior conversion to the standard of their respective operating system. Except for the above characters, only printable characters (i.e., ASCII codes `0x20`, ..., `0x7f`) are permitted as part of an ANTEX file. While technically possible, characters in the upper byte range (`0x80`, ..., `0xFF`), which are commonly used for language-specific symbols, are not officially supported and may cause incompatibilities in the exchange of ANTEX files.

As their core element, ANTEX files are composed of labeled parameter lines and section markers with a nominal length of 80 characters. The predefined labels are placed in cols. 61 – 80, with no leading blanks. Trailing blanks, on the other hand may be omitted, and readers need to be able to handle lines with less than the nominal 80 characters. All labels as defined in the ANTEX standard are based on capital letters (A, ..., Z) along with blanks (' '), slashes ('/'), and hash symbols ('#'). Individual parameter lines comprise one or multiple integer-valued, float-valued, or string parameters at predefined fields of the first 60 characters of that line. The set of data contained in a given line is described by the corresponding label, which uses slashes to identify multiple parameters in a single line.

Section markers are a special form of labeled lines with a section-specific '`START OF ...`' or '`END OF ...`' label in cols. 61, ..., 80, which initiates or terminates a given data section. Depending on the type of section, the section marker lines may themselves include specific parameters related to the respective section or comprise an all-blank field in cols. 1, ..., 60.

Comment lines serve for documentary purposes and should be used to provide background information that is not covered by file- and antenna-related metadata in an ANTEX file. In analogy with the parameter lines, comment lines are identified by the label `COMMENT` starting in column 61 and may comprise free text in cols. 1, ..., 60 within the general conditions described above. Use of mixed (upper-lower) case is specifically encouraged for improved readability. File- and antenna-related comments may be inserted in the respective header sections as specified in further detail below.

Empty lines are not permitted inside any of the header and antenna sections. However, empty lines may be inserted between such sections to better distinguish individual antennas in human reading.

For the actual antenna pattern data, lines exceeding the 80-character limit of the labeled header and parameter lines may arise. The actual line length depends on the total number of grid points for the off-boresight angle and no fixed limit is presently defined.

3.2 Antenna Type Names

Type names of satellite and receiver antennas in ANTEX files are encoded as 20-char strings. IGS-specific conventions for receiver and satellite (transmit) antenna type names are discussed in Sect. 4.1.

3.3 Frequency Band Identifiers

The various antenna characteristics (phase, code, and gain patterns) described in an ANTEX file depend on the frequency and partly the modulation characteristics of the individual GNSS signals. Associated calibrations need to be performed over a set of actual GNSS signals or are representative set of continuous wave carriers. For consistency with its predecessor, the ANTEX 2.0 format utilizes dedicated frequency band identifiers, which are intended to represent constellation-specific sets of signals and can easily be derived from signal codes as used in Receiver INdependent EXchange (RINEX) (Gini, 2024) observation files.

Table 1. Table of center frequencies and constellation-specific frequency band identifiers

Frequency [MHz]	Description	GPS	GLONASS	Galileo	BeiDou	QZSS	NavIC	SBAS
2492.028	S band						I09	
1602.000	GLO L1 band (FDMA)		R01					
1600.995	GLO L1 band (CDMA)		R04					
1575.420	L1/E1/B1 band	G01		E01	C01	J01	I01	S01
1561.098	B1-2 band				C02			
1278.750	E6 band			E06		J06		
1268.520	B3 band				C06			
1248.065	GLO L2 band (CDMA)		R06					
1246.000	GLO L2 band (FDMA)		R02					
1227.600	L2 band	G02				J02		
1207.140	E5b/B2b band			E07	C07			
1202.025	GLO L3 band		R03					
1191.795	E5a+b/B2a+b band			E08	C08			
1176.450	L5/E5a/B2a band	G05		E05	C05	J05	I05	S05

Table 1 provides a list of all currently supported frequency band identifiers. They are made up a single letter (G, R, E, C, J, I, S) identifying the respective constellation, as well as a two digit frequency band number. The constellation letters match the ones defined for satellite identifiers (PRN or slot number) in the SP3 (Hilla, 2016) ephemeris format and the RINEX observation data format. By convention, the ANTEX frequency band number is limited to single-digit values ($n < 10$) and matches the band/frequency designator used in the corresponding RINEX observation codes. As such, the leading (left-most) digit of the ANTEX frequency band number is always set to zero.

For completeness, we note that the use of a frequency band identifier for distinguishing individual calibration data sets in ANTEX 2.0 implies a partly limited granularity of the associated antenna calibrations. On the one hand, it is not possible to account for individual center frequencies of the legacy frequency division multiple access (FDMA) signals used by GLONASS in the L1 and L2 bands. For code division multiple access (CDMA) signals, on the other hand, the frequency band identifier does not allow to distinguish signals with different modulations but common center frequency, such as the 1 MHz L1 C/A code signal and the 10 MHz L1 P(Y) signal. While this is a known limitation motivated by the interest of maintaining backwards compatibility and avoiding an overly complexity, the practical limitations are considered tolerable for most users and applications.

3.4 File Structure

Each ANTEX file is made up of a hierarchical set of header and data records providing selected sets of antenna information (Fig. 3). Following the file start marker and a header with file-related metadata, a list of individual antenna records is provided, which may be separated by one or more blank lines. Each antenna record comprises a full set of antenna calibration data for a single satellite or receiver antenna and is itself made up of one or multiple calibration records. A single calibration record covers antenna data of a common type (i.e., either phase, or code, or gain calibrations) with a common pattern grid and validity interval as specified in the respective calibration record header. A sequence of individual calibration records within the antenna record is used to specify the different types of data and/or calibrations for multiple validity intervals. The data part of the calibration record comprises a set of frequency records, each of which combines the pattern and offset for a given set of frequency bands identified in the start marker line.

Frequency records within a calibration record, calibration records within an antenna record and antenna records do not need to adhere to a specific order, but must be non-overlapping and non-redundant to enable an unambiguous and conflict-free access to antenna information for a given antenna, calibration data type, time of interest, and frequency band.

Further information including practical hints for generating and processing ANTEX 2.0 files are provided in Sect. 4. Furthermore, that section describes IGS-specific conventions that need to be followed for ANTEX files maintained and used by the IGS.

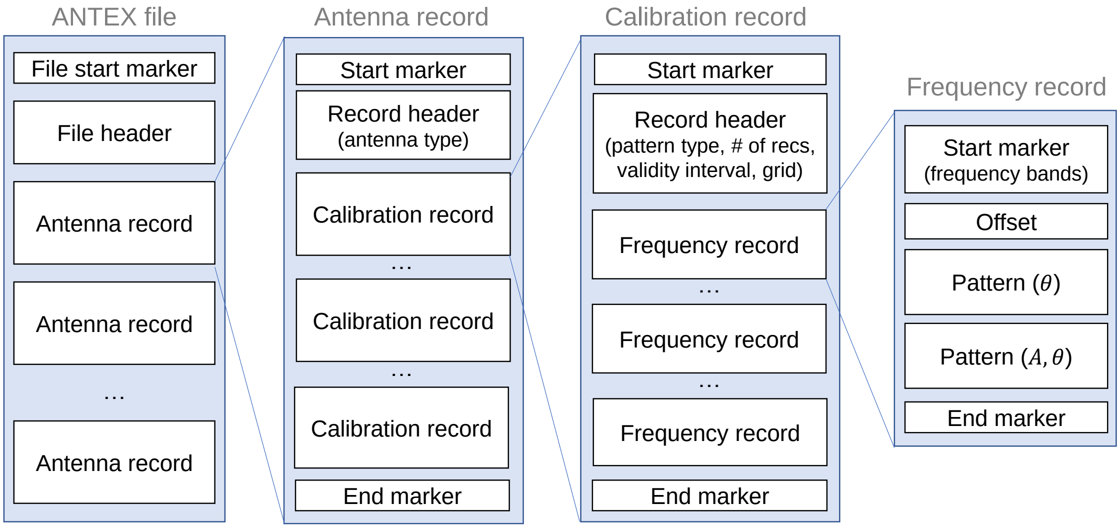

Fig. 3. Schematic view of the ANTEX 2.0 file structure.

3.5 Detailed Format Specification

3.5.1 File Header

The ANTEX file starts with an 'ANTEX VERSION' record identifying the file type and format version. The subsequent file header is initiated by a 'START OF HEADER' record and terminated by the 'END OF HEADER' line. Inside the header section, various mandatory records with file metadata as well as optional comment records are provided in arbitrary order. A list of currently supported header records is given in Table 2. Users should make provisions to tolerate the presence of other metadata records that might be added in future versions. Comment records may be inserted at any position of the file header section. A formal specification of the ANTEX 2.0 start and file header is given in Table 2, a sample file header is shown in Listing 1.

Table 2. Specification of the ANTEX file header

Label	**Description**	**Parameter Format**
`ANTEX VERSION`	Format version (2.0) This record must be given as the first line of the ANTEX file.	F8.1, 52X
`START OF HEADER`	This line initiates the ANTEX file header (mandatory)	60X
`ANTENNA TYPES`	`SATELLITE`, `RECEIVER`, or `MIXED` for ANTEX files providing only satellite antennas, only receiver antennas, or both antenna types (optional)	A10, 50X
`REFERENCE FRAME`	Frame identifier (e.g., `IGS20`) indicating the terrestrial reference frame (TRF) scale implied by the satellite PCOs; use `MIXED` if PCOs of different constellations refer to different TRF scales (optional)	A10, 50X
`RELEASE`	Year and day of year of file release date (mandatory)	I4, I3.3, 53X
`COMMENT`	Comment record with free text (optional; multiple records permitted)	A60
`END OF HEADER`	End-of-header record (mandatory). This record closes the header section. Following it, no further header records are permitted.	60X

Listing 1. ANTEX file header example. Column numbers have been added for illustration only and are not part of the actual data.

```
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
     2.0                                                    ANTEX VERSION
                                                            START OF HEADER
#                                                           COMMENT
# ANTEX 2.0 version of igs20_2317_sat.atx                   COMMENT
#                                                           COMMENT
SATELLITE                                                   ANTENNA TYPES
IGS20                                                       REFERENCE FRAME
2024154                                                     RELEASE
                                                            END OF HEADER
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
```

3.5.2 Antenna Record

Each antenna record starts with a parameter-less 'START OF ANTENNA' line and is terminated by the 'END OF ANTENNA' line. Following a 'TYPE / SVN' or 'TYPE / SN', which identifies the specific satellite or receiver antenna type as well as optional antenna comments, the main body of the antenna section provides a sequence of calibration records for the various pattern types and validity intervals (Table 3).

Table 3. Specification of the antenna record. The sequence of individual parameter, data, and comment lines within the antenna record (whether mandatory or optional) is expected to match the listed order.

Label	Description	Parameter Format
START OF ANTENNA	Start of antenna record (mandatory)	60X
	Description of the antenna type and related information (mandatory 1st line of the antenna record). Either of the following two versions (for satellite and receiver antennas, respectively) must be provided:	
TYPE / SVN	This label identifies a satellite (transmit) antenna and comprises two parameters: - Antenna name (see Sect. 3.2) - Space vehicle number (SVN) for satellite-specific patterns (blank for block-specific patterns)	 A20, 20X, A4,16X
or TYPE / SN	This label identifies a receiver antenna and comprises two parameters: - Combined antenna and (optional) radome name (see Sect. 3.2) - Serial number (blank for type-specific patterns)	 A20, A20, 20X
ORIGIN	This record is provided for satellite transmit antennas to indicate, whether code and phase center offsets are referred to the center of mass (parameter value 'COM') or a predefined antenna reference point (parameter value 'ARP') in the satellite body frame. For satellite transmit antennas, the record is mandatory and provided as the third line of the antenna records. For receiver antennas, the record is absent.	A3,57X
COMMENT	Comment record with free text (optional; multiple records permitted)	A60
... One or more calibration records ...		
END OF ANTENNA	End-of-antenna marker (mandatory). This line closes the antenna record. Following it, only blank lines or other antenna sections are permitted.	60X

3.5.3 Calibration Record

Individual calibration records within an antenna record are initiated by a START OF CALIB marker and terminated by an END OF CALIB marker. Each calibration record is made up of a calibration record header providing selected metadata and a sequence of individual frequency records (Table 4). The latter provide antenna patterns of a given type (i.e., carrier phase, group delay, or gain patterns) for individual frequency bands on a given grid as specified in the calibration record header. The calibration record header also defines the type and number of frequency records within the calibration record, which may be used for basic integrity checks when processing an ANTEX file. Consecutive calibration records within an antenna record are used to provide patterns with different type, grid, and validity interval.

Following the end of a calibration record, either a new calibration record or an END OF ANTENNA marker must be provided. Selected examples of antenna records for GNSS satellite antennas and receiver antennas are provided in listings 2 and 3.

Table 4. Specification of the calibration record. The sequence of individual parameter, data, and comment lines within the calibration record (whether mandatory or optional) is expected to match the listed order.

Label	**Description**	**Parameter Format**
`START OF CALIB`	Start of calibration record (mandatory)	60X
`TYPE / # OF FREQS`	Mandatory first line of calibration record specifying the type and number of frequency records within the current calibration record - Calibration data type identifier (left-justified) `PHASE` for phase calibration data `CODE` for code calibration data `GAIN` for gain calibration data - Number of frequency records (n_F) within the current calibration record	 A10, I6, 44X
`METH / BY / # / DATE`	Specification of calibration-related metadata (mandatory second line of calibration record) - Calibration method: '`CHAMBER`', '`CONVERTED`', '`COPIED`', '`ESTIMATED`', '`FIELD`', '`SCALE_ADJUSTED`', '`ROBOT`', or blank (see Sect. 4.2) - Name of agency (or blank) - Number of individual antennas calibrated (blank if unknown) - Date in format yyyy/mm/dd	 A20, A20, I6, 4X, A10
`VALID FROM`	Start of validity period in GPS Time (4-digit year, month, day, hour, min, sec). Optional, only needed if antenna characteristics change over time.	5I6, F13.7, 17X
`VALID UNTIL`	End of validity period in GPS Time (4-digit year, month, day, hour, min, sec). Optional, only needed if antenna characteristics change over time.	5I6, F13.7, 17X
`DAZI`	Azimuth step size $\Delta A > 0°$ (in [°]) of the equidistant antenna pattern grid (mandatory). The grid is assumed to cover azimuth angles ranging from $A_{\text{low}} = 0°$ (first point) to $A_{\text{upp}} = 360°$ (last point) with a total of $n+1$ grid points, where $n = 360°/\Delta A$ is an integer value. A value of $\Delta A = 360°$ is used for antenna patterns that vary only with the off-boresight angle θ.	2X, F6.1, 52X
`ZEN1 / ZEN2 / DZEN`	Definition of the off-boresight angle grid (mandatory): - Lower bound $\theta_{\text{low}} = 0°$ in [°] - Upper bound θ_{upp} in [°] - Step size $\Delta\theta$ in [°]. where $\Delta\theta > 0$ and the upper bound is an integer multiple $\theta_{\text{upp}} = m \cdot \Delta\theta$ of the step size. The total number of grid points in θ amounts to $m+1$.	2X, 3F6.1, 40X
`COMMENT`	Comment record with free text (optional; multiple records permitted)	A60
... n_F frequency records (mandatory) ...		
`END OF CALIB`	End of calibration record (mandatory)	60X

3.5.4 Frequency Record

Individual frequency records are initiated by a '`START OF xxxx`' line and terminated by a corresponding '`END OF xxxx`' line, where '`xxxx`' identifies the respective pattern type. Supported labels are '`PHASE`' for carrier phase patterns, '`CODE`' for group delay patterns, and '`GAIN`'. Thereafter, the respective antenna pattern is tabulated in a fixed-format matrix for the specified (A, θ) grid. At the start of each line of the pattern matrix, the corresponding azimuth value is given, which may be used to check the integrity of an antenna record. For grid points with a missing or unknown pattern value a blank entry may be provided instead of number in the respective cell of the pattern table. Practical hints on handling such data are provided in Sect. 4.3.

The detailed content and layout of the three types of frequency records are specified in Tables 5, 6, and 7. Examples of calibration records and frequency records for GNSS satellite antennas and receiver antennas are provided in listings 2 and 3.

Table 5. Specification of a frequency record with phase pattern data for a set of frequency bands

Label	Description	Parameter Format
`START OF PHASE`	First line of the frequency record for phase calibration data (mandatory). The parameters specify a list of $1 \leq n_f \leq 10$ constellation-wise frequency bands (see Sect. 3.3) for which this pattern can be applied.	$n_f \times$(3X,A1,I2.2), $(54 - 6n_f)\times$X
`X / Y / Z`	Components of the phase center offset ($\Delta \boldsymbol{r}_{\mathrm{PCO}}$, in [mm]) in the antenna reference frame (second line of record; mandatory)	3F10.2, 30X
	Table of azimuth values A_i and azimuth-dependent phase variations $\Delta\zeta_{i,j} = \Delta\zeta(A_i, \theta_j)$ (mandatory; all values in [mm]) for $n{+}1$ azimuth grid points $A_i = i \cdot \Delta A$ $(i = 0, \ldots, n)$ and $m{+}1$ off-boresight angles $\theta_j = j \cdot \Delta\theta$ $(j = 0, \ldots, m)$ $0^\circ \quad \Delta\zeta(0^\circ, 0^\circ) \quad \Delta\zeta(0^\circ, \Delta\theta) \quad \ldots \quad \Delta\zeta(0^\circ, \theta_{\mathrm{upp}})$ $\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots$ $A_i \quad \Delta\zeta(A_i, 0^\circ) \quad \Delta\zeta(A_i, \Delta\theta) \quad \ldots \quad \Delta\zeta(A_i, \theta_{\mathrm{upp}})$ $\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots$ $360^\circ \quad \Delta\zeta(360^\circ, 0^\circ) \quad \Delta\zeta(360^\circ, \Delta\theta) \quad \ldots \quad \Delta\zeta(360^\circ, \theta_{\mathrm{upp}})$ (one line per azimuth angle). The table starts in the 3rd line of the frequency record and comprises at least two lines. No line-length limit applies for the table of pattern values. Missing values are indicated by blanks.	 F8.1, $(m{+}1)\times$[F8.2 or 8X] $\vdots$ F8.1, $(m{+}1)\times$[F8.2 or 8X] $\vdots$ F8.1, $(m{+}1)\times$[F8.2 or 8X]
`END OF PHASE`	End-of-frequency record marker (mandatory). This line closes the frequency record for phase calibration data. Following it, only a subsequent frequency record, a new calibration record header, and an `END OF ANTENNA` record are permitted.	60X

Table 6. Specification of a frequency record with group delay pattern data for a set of frequency bands

Label	Description	Parameter Format
`START OF CODE`	First line of the frequency record for code calibration data (mandatory). The parameters specify a list of $1 \le n_f \le 10$ constellation-wise frequency bands (see Sect. 3.3) for which this pattern can be applied.	 $n_f \times$(3X,A1,I2.2), $(54-6n_f)\times$X
`X / Y / Z`	Components of the code center offset ($\Delta\boldsymbol{r}_{\text{CCO}}$, in [mm]) in the antenna reference frame (second line of record; mandatory)	3F10.1, 30X
	Table of azimuth values A_i and azimuth-dependent group delay variations $\Delta\xi_{i,j} = \Delta\xi(A_i, \theta_j)$ (mandatory; all values in [mm]) for $n{+}1$ azimuth grid points $A_i = i \cdot \Delta A$ $(i = 0, \ldots, n)$ and $m{+}1$ off-boresight angles $\theta_j = j \cdot \Delta\theta$ $(j = 1, \ldots, m)$ 0° $\Delta\xi(0^\circ, 0^\circ)$ $\Delta\xi(0^\circ, \Delta\theta)$ $\ldots$ $\Delta\xi(0^\circ, \theta_{\text{upp}})$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ A_i $\Delta\xi(A_i, 0^\circ)$ $\Delta\xi(A_i, \Delta\theta)$ $\ldots$ $\Delta\xi(A_i, \theta_{\text{upp}})$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ 360° $\Delta\xi(360^\circ, 0^\circ)$ $\Delta\xi(360^\circ, \Delta\theta)$ $\ldots$ $\Delta\xi(360^\circ, \theta_{\text{upp}})$ (one line per azimuth angle). The table starts in the 3rd line of the frequency record and comprises at least two lines. No line-length limit applies for the table of pattern values. Missing values are indicated by blanks.	 F8.1, $(m{+}1)\times$[F8.1 or 8X] $\vdots$ F8.1, $(m{+}1)\times$[F8.1 or 8X] $\vdots$ F8.1, $(m{+}1)\times$[F8.1 or 8X]
`END OF CODE`	End-of-frequency record marker (mandatory). This line closes the frequency record for code calibration data. Following it, only a subsequent frequency record, a new calibration record header, and an `END OF ANTENNA` record are permitted.	60X

Table 7. Specification of a frequency record with gain calibration data for a set of frequency bands

Label	Description	Parameter Format
`START OF GAIN`	First line of the frequency record for gain calibration data. The parameters specify a list of $1 \le n_f \le 10$ constellation-wise frequency bands (see Sect. 3.3) for which this pattern can be applied.	 $n_f \times$(3X,A1,I2.2), $(54-6n_f)\times$X
`OFFSET`	Common gain offset (ΔG, in [dB]) (second line of record; mandatory)	3F10.2, 30X
	Table of azimuth values A_i and azimuth-dependent antenna gains $\Delta G_{i,j} = \Delta G(A_i, \theta_j)$ (mandatory; all values in [dB]) for $n{+}1$ azimuth grid points $A_i = i \cdot \Delta A$ $(i = 0, \ldots, n)$ and $m{+}1$ off-boresight angles $\theta_j = j \cdot \Delta\theta$ $(j = 1, \ldots, m)$ 0° $\Delta G(0^\circ, 0^\circ)$ $\Delta G(0^\circ, \Delta\theta)$ $\ldots$ $\Delta G(0^\circ, \theta_{\text{upp}})$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ A_i $\Delta G(A_i, 0^\circ)$ $\Delta G(A_i, \Delta\theta)$ $\ldots$ $\Delta G(A_i, \theta_{\text{upp}})$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ $\vdots$ 360° $\Delta G(360^\circ, 0^\circ)$ $\Delta G(360^\circ, \Delta\theta)$ $\ldots$ $\Delta G(360^\circ, \theta_{\text{upp}})$ (one line per azimuth angle). The table starts in the 3rd line of the frequency record and comprises at least two lines. No line-length limit applies for the table of pattern values. Missing values are indicated by blanks.	 F8.1, $(m{+}1)\times$[F8.2 or 8X] $\vdots$ F8.1, $(m{+}1)\times$[F8.2 or 8X] $\vdots$ F8.1, $(m{+}1)\times$[F8.2 or 8X]
`END OF GAIN`	End-of-frequency record marker (mandatory). This line closes the frequency record for gain patterns. Following it, only a subsequent frequency record, a new calibration record header, and an `END OF ANTENNA` record are permitted.	60X

Listing 2. Satellite antenna record with carrier phase and gain patterns for three frequency bands. Column numbers have been added for illustration only and are not part of the actual data. Colored bars indicate the antenna record header (orange), the calibration record header (green), and the frequency records (blue).

```
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8----+----9----+----0----+----1----+----2----+----3
                                                            START OF ANTENNA
LANT_GPS_III                            G074                TYPE / SVN
COM                                                         ORIGIN
#                                                           COMMENT
# Fischer A; GPS III Earth Coverage (EC) Antenna Patterns   COMMENT
# Lockheed Martin Corporation (2022)                        COMMENT
# (PHV interpolated to 1 deg steps in off-boresight angle)  COMMENT
#                                                           COMMENT
                                                            START OF CALIB
PHASE          3                                            TYPE / # OF FREQS
CHAMBER             LOCKHEED MARTIN          1    2022/05/01METH / BY / # / DATE
  2019    01    09    00    00   00.0000000                 VALID FROM
    10.0                                                    DAZI
     0.0  14.0   1.0                                        ZEN1 / ZEN2 / DZEN
   G01                                                      START OF PHASE
    -59.94     17.48   1090.45                              X / Y / Z
     0.0    7.24    6.68    5.60    3.64    0.96   -2.07   -4.91   -7.01   -8.07   -7.90   -6.57   -4.20   -0.91    3.20    8.05
    10.0    7.24    6.66    5.55    3.54    0.83   -2.20   -5.00   -7.03   -8.02   -7.81   -6.45   -4.07   -0.79    3.28    8.10
...
   350.0    7.24    6.69    5.65    3.72    1.06   -1.99   -4.88   -7.05   -8.18   -8.07   -6.76   -4.39   -1.08    3.07    7.98
   360.0    7.24    6.68    5.60    3.64    0.96   -2.07   -4.91   -7.01   -8.07   -7.90   -6.57   -4.20   -0.91    3.20    8.05
                                                            END OF PHASE
   G02                                                      START OF PHASE
    -59.26     15.60    598.47                              X / Y / Z
     0.0    4.02    3.82    3.43    2.66    1.49   -0.08   -1.92   -3.81   -5.36   -6.15   -5.92   -4.50   -1.88    1.90    6.74
    10.0    4.02    3.82    3.43    2.67    1.50   -0.07   -1.94   -3.88   -5.50   -6.37   -6.24   -4.91   -2.38    1.31    6.07
...
   350.0    4.02    3.82    3.42    2.64    1.46   -0.10   -1.91   -3.74   -5.22   -5.93   -5.63   -4.16   -1.50    2.29    7.13
   360.0    4.02    3.82    3.43    2.66    1.49   -0.08   -1.92   -3.81   -5.36   -6.15   -5.92   -4.50   -1.88    1.90    6.74
                                                            END OF PHASE
   G05                                                      START OF PHASE
    -59.33     15.67    636.70                              X / Y / Z
     0.0    3.42    3.27    2.97    2.36    1.44    0.23   -1.20   -2.71   -4.01   -4.82   -4.84   -3.87   -1.81    1.38    5.68
    10.0    3.42    3.26    2.93    2.30    1.35    0.11   -1.33   -2.83   -4.12   -4.92   -4.98   -4.06   -2.08    1.01    5.21
...
   350.0    3.42    3.29    2.99    2.40    1.48    0.26   -1.17   -2.67   -3.96   -4.74   -4.73   -3.70   -1.59    1.62    5.88
   360.0    3.42    3.27    2.97    2.36    1.44    0.23   -1.20   -2.71   -4.01   -4.82   -4.84   -3.87   -1.81    1.38    5.68
                                                            END OF PHASE
                                                            END OF CALIB
                                                            START OF CALIB
GAIN           3                                            TYPE / # OF FREQS
CHAMBER             LOCKHEED MARTIN          1    2022/05/01METH / BY / # / DATE
  2019    01    09    00    00   00.0000000                 VALID FROM
    10.0                                                    DAZI
     0.0  14.0   2.0                                        ZEN1 / ZEN2 / DZEN
   G01                                                      START OF GAIN
     -1.00                                                  OFFSET
     0.0   14.68   14.38   13.89   14.06   14.98   15.87   16.15   15.54
    10.0   14.68   14.37   13.92   14.11   15.01   15.85   16.07   15.45
...
   350.0   14.68   14.38   13.88   14.02   14.95   15.88   16.19   15.62
   360.0   14.68   14.38   13.89   14.06   14.98   15.87   16.15   15.54
                                                            END OF GAIN
   G02                                                      START OF GAIN
     -1.00                                                  OFFSET
     0.0   15.28   15.03   14.42   13.76   13.53   13.85   14.33   14.55
    10.0   15.28   15.02   14.40   13.72   13.48   13.82   14.32   14.53
...
   350.0   15.28   15.04   14.45   13.80   13.58   13.89   14.36   14.59
   360.0   15.28   15.03   14.42   13.76   13.53   13.85   14.33   14.55
                                                            END OF GAIN
   G05                                                      START OF GAIN
     -1.00                                                  OFFSET
     0.0   14.72   14.52   14.05   13.53   13.31   13.53   13.97   14.26
    10.0   14.72   14.52   14.05   13.54   13.30   13.47   13.82   14.03
...
   350.0   14.72   14.52   14.04   13.52   13.32   13.58   14.06   14.37
   360.0   14.72   14.52   14.05   13.53   13.31   13.53   13.97   14.26
                                                            END OF GAIN
                                                            END OF CALIB
                                                            END OF ANTENNA
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8----+----9----+----0----+----1----+----2----+----3
```

Listing 3. Receiver antenna record with carrier phase and gain patterns for three frequency bands. Column numbers have been added for illustration only and are not part of the actual data. Colored bars indicate the antenna record header (orange), the calibration record header (green), and the frequency records (blue).

```
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8----+----9----+----0----+----1----+----2----+----3
                                                            START OF ANTENNA
PEC2CR          NONESN99                                    TYPE / SN
#                                                           COMMENT
# Receiver antenna example                                  COMMENT
#                                                           COMMENT
                                                            START OF CALIB
PHASE          3                                            TYPE / # OF FREQS
CHAMBER             COMPANY LTD.             1    2017/09/12METH / BY / # / DATE
    10.0                                                    DAZI
     0.0  90.0   2.0                                        ZEN1 / ZEN2 / DZEN
   G01   E01                                                START OF PHASE
      0.64      0.64     96.56                              X / Y / Z
     0.0    0.70    0.70    0.69    0.67    0.64    0.60     ...    1.19    1.55    1.95    2.41    2.92    3.48    4.10    4.78
     ...
   360.0    0.70    0.70    0.69    0.67    0.64    0.60     ...    1.19    1.55    1.95    2.41    2.92    3.48    4.10    4.78
                                                            END OF PHASE
   G02   E06                                                START OF PHASE
      0.64      0.72    101.85                              X / Y / Z
     0.0    0.76    0.77    0.76    0.75    0.72    0.69     ...    0.29    0.47    0.67    0.89    1.13    1.40    1.70    2.02
     ...
   360.0    0.76    0.77    0.76    0.75    0.72    0.69     ...    0.29    0.47    0.67    0.89    1.13    1.40    1.70    2.02
                                                            END OF PHASE
   G05   E05   E07   E08                                    START OF PHASE
      0.70      0.62    113.66                              X / Y / Z
     0.0    1.22    1.22    1.21    1.18    1.14    1.08     ...    1.00    1.42    1.87    2.38    2.94    3.53    4.17    4.84
     ...
   360.0    1.22    1.22    1.21    1.18    1.14    1.08     ...    1.00    1.42    1.87    2.38    2.94    3.53    4.17    4.84
                                                            END OF PHASE
                                                            END OF CALIB
                                                            START OF CALIB
CODE           3                                            TYPE / # OF FREQS
CHAMBER             RUAG                     1    2017/09/12METH / BY / # / DATE
    10.0                                                    DAZI
     0.0  90.0   2.0                                        ZEN1 / ZEN2 / DZEN
   G01   E01                                                START OF CODE
      -1.9       0.8     137.9                              X / Y / Z
     0.0     6.6     6.6     6.6     6.5     6.4     6.2     ...    17.7    21.8    25.6    28.6    30.8    31.7    31.1    28.7
     ...
   360.0     6.6     6.6     6.6     6.5     6.4     6.2     ...    17.7    21.8    25.6    28.6    30.8    31.7    31.1    28.7
                                                            END OF CODE
   G02   E06                                                START OF CODE
       1.2      -0.5     279.1                              X / Y / Z
     0.0     3.7     3.9     4.2     4.5     4.8     5.2     ...    11.8    18.4    25.5    33.0    40.9    49.0    57.5    66.1
     ...
   360.0     3.7     3.9     4.2     4.5     4.8     5.2     ...    11.8    18.4    25.5    33.0    40.9    49.0    57.5    66.1
                                                            END OF CODE
   G05   E05   E07   E08                                    START OF CODE
       3.7      -8.5     508.0                              X / Y / Z
     0.0    14.0    14.1    14.1    13.9    13.5    12.9     ...    10.8    10.8     9.8     7.8     4.4    -0.5    -7.2   -15.9
     ...
   360.0    14.0    14.1    14.1    13.9    13.5    12.9     ...    10.8    10.8     9.8     7.8     4.4    -0.5    -7.2   -15.9
                                                            END OF CODE
                                                            END OF CALIB
                                                            START OF CALIB
GAIN           3                                            TYPE / # OF FREQS
CHAMBER             COMPANY LTD.             1    2017/09/12METH / BY / # / DATE
    10.0                                                    DAZI
     0.0  90.0   2.0                                        ZEN1 / ZEN2 / DZEN
   G01   E01                                                START OF GAIN
      0.00                                                  OFFSET
     0.0    8.97    8.96    8.93    8.87    8.78    8.68     ...   -4.83   -5.41   -5.99   -6.57   -7.15   -7.73   -8.29   -8.85
     ...
   360.0    8.97    8.96    8.93    8.87    8.78    8.68     ...   -4.83   -5.41   -5.99   -6.57   -7.15   -7.73   -8.29   -8.85
                                                            END OF GAIN
   G02   E06                                                START OF GAIN
      0.00                                                  OFFSET
     0.0    8.20    8.19    8.16    8.10    8.03    7.94     ...   -3.35   -3.84   -4.33   -4.82   -5.30   -5.79   -6.28   -6.76
     ...
   360.0    8.20    8.19    8.16    8.10    8.03    7.94     ...   -3.35   -3.84   -4.33   -4.82   -5.30   -5.79   -6.28   -6.76
                                                            END OF GAIN
   G05   E05   E07   E08                                    START OF GAIN
      0.00                                                  OFFSET
     0.0    7.80    7.79    7.75    7.70    7.63    7.53     ...   -3.69   -4.15   -4.61   -5.05   -5.49   -5.91   -6.32   -6.71
     ...
   360.0    7.80    7.79    7.75    7.70    7.63    7.53     ...   -3.69   -4.15   -4.61   -5.05   -5.49   -5.91   -6.32   -6.71
                                                            END OF GAIN
                                                            END OF CALIB
                                                            END OF ANTENNA
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8----+----9----+----0----+----1----+----2----+----3
```

4 Conventions and Explanations

4.1 IGS Conventions for Antenna Type Names

Beyond the general ANTEX formatting rules, various additional conventions apply for antennas considered in the IGS antenna model. Here, only upper case letters (`A, ..., Z`), roman numerals (`0, ..., 9`), blanks, as well as plus (+), minus (−), slash (/), underscore (_), and period (.) characters are permitted in the type names of satellite and receiver antennas.

In the case of receiver antennas, the ANTEX antenna name is partitioned into two fields, where the first 15 characters designate the actual antenna model, while the last four characters designate the radome type. Both fields are separated by a blank character in col. 16. Aside from this, only trailing blanks are permitted in the substrings identifying the antenna model and radome. For use within the IGS, a conventional set of receiver antenna/radome names is defined in IGS (2025a) to ensure a consistent naming across different users and analysis centers. Among others, the first three characters of IGS receiver antenna names represent a unique vendor code. The IGS `rcv_ant.tab` file listing all supported antennas is continuously updated as new antenna models and calibrations are made available for the IGS network and general users.

IGS satellite antenna type names as used in ANTEX 1.x were defined by the IGS Antenna Working Group. They cover a length of up to 15 characters and are documented in IGS (2025a). Except for the '`BLOCK xxxxx`' names of GPS satellite antennas, blanks are not used/permitted in the legacy type names. With the introduction of ANTEX 2.0, a new set of satellite antenna names has been introduced, which harmonizes the naming of antennas across different constellations and supports multiple GNSS. antennas on a single satellite. The new antenna types names are defined in IGS (2025d) and may have a length of up to 20 characters without blanks. Permitted characters comprise upper case letters, roman numerals, as well as underscores and plus signs. As a general rule, the new satellite antenna names are composed of a generic antenna label (e.g., `LANT` or `L5SANT`) related to the purpose and transmitted signals of the antenna and the block name of the satellite as used in the IGS satellite metadata file (Steigenberger and Montenbruck, 2024; IGS, 2025b).

4.2 IGS Conventions for Calibration Methods

Within the IGS, a predefined set of keywords is used to indicate the calibration method of a satellite or receiver antenna. The meaning of these keywords and the respective calibration approach are described below:

- `CHAMBER`: Calibration in an anechoic chamber with unmodulated radio waves or artificial GNSS signals (e.g., Zeimetz and Kuhlmann, 2008).

- `CONVERTED`: Deprecated keyword for historic antennas calibrations obtained from the combination of several GPS calibration campaigns and chamber measurements (Rothacher and Mader, 1996).

- `COPIED`: Copied from another calibration of a similar antenna setup. Typically used if a calibration of a dedicated antenna/radome combination is not available.

- `ESTIMATED`: Transmit antenna phase patterns and PCOs estimated from observations of a global GNSS tracking network (e.g., Schmid et al, 2007)

- `FIELD`: Relative field calibrations w.r.t. the reference antenna `AOAD/M_T` (e.g., Mader, 1999); converted to absolute calibrations by adding the phase center offsets and patterns of the reference antenna.

- `SCALE_ADJUSTED`: The transmit antenna z-PCOs obtained from chamber calibrations are shifted by a constant value per satellite group to be consistent with the scale of a dedicated reference frame (Villiger et al, 2020).

- ROBOT: The antenna under test is tilted and rotated by a robot and real GNSS signals are used for the calibration (e.g., Menge et al, 1998).

4.3 Practical Hints

Complementary to the formal format specification in Sect. 3, this section provides additional guidance for the generation and processing of ANTEX 2.0 antenna models:

- Users should be prepared to handle labeled parameter lines and section markers with a length of less than 80 chars, if trailing blanks have been stripped in the ANTEX file generation.

- Within the ANTEX 2.0 format, all antenna patterns are consistently represented as 2-dimensional azimuth / off-boresight angle grids. The complementary and redundant specification of an azimuth-averaged (NOAZI) pattern used in ANTEX 1.x is no longer required and supported. Antenna patterns that depend only on the off-boresight angle are described by two azimuth grid points ($A_0 = 0°$ and $A_1 = 360°$) with a grid spacing of $\Delta A = 360°$.

- ANTEX 2.0 allows for missing/unknown values in the tabulated pattern data. The respective entries of the pattern table in a 'PHASE', 'CODE', or 'GAIN' frequency record are indicated by a blank string instead of a numerical value. Users must be prepared to handle such data when reading and processing an ANTEX file. For practical purposes, missing data may be replaced by zeroes or the not a number (NaN)floating point value representation supported by common programming languages.

- The ANTEX 2.0 format is specifically designed to facilitate bi-linear interpolation. For any pair (A, θ) of azimuth and off-boresight values with $0° \leq A < 360°$ and $\theta < \theta_{\text{upp}}$, the interpolated value of a pattern X can be obtained from the tabulated values as

  $$X(A, \theta) = p \cdot q \cdot X_{i,j} + (1-p) \cdot q \cdot X_{i+1,j} + p \cdot (1-q) \cdot X_{i,j+1} + (1-p) \cdot (1-q) \cdot X_{i+1,j+1} \tag{13}$$

  with grid point indices

  $$i = \text{trunc}\,[A/\Delta A] \quad \text{and} \quad j = \text{trunc}\,[\theta/\Delta\theta] \tag{14}$$

  as well as the fractional steps

  $$p = A/\Delta A - i \quad \text{and} \quad q = \theta/\Delta\theta - j \tag{15}$$

  with $0 \leq p, q < 1$.

- Antenna models for satellite transmit antennas may include both satellite-specific and type-specific (block-average) antenna data. Within the ANTEX file, the specific model type is indicated by the presence or absence of a space vehicle number in the 'TYPE / SVN' line of the antenna record header (cf. Table 3). Accordingly, the user software for processing of ANTEX files must provide distinct look-up functions for searching satellite antennas by antenna type name and SVN (for satellite-specific data) as well as antenna type name only (for type-specific data).

- Antenna models for receiver antennas may include both device-specific and type-specific (group-average) antenna data. Within the ANTEX file, the specific model type is indicated by the presence or absence of a serial number (SN) in the 'TYPE / SN' line of the antenna record header (cf. Table 3). Accordingly, the user software for processing of ANTEX files must provide distinct look-up functions for searching receiver antennas by antenna type name and SN (for device-specific data) as well antenna type name only (for type-specific data).

- GNSS pseudo-range and carrier phase measurements in RINEX observation files, Radio Technical Commission for Maritime Services (RTCM) real-time streams, or receiver-specific binary data formats are commonly identified by the PRN or slot number of the transmitting satellite as well as a unique code for the tracked signal. For modeling of antenna-related range corrections based on ANTEX 2.0 antenna models, the SVN of the transmitting satellite must first be obtained. Corresponding look-up tables are provided as part of the IGS satellite metadata file (IGS, 2025b; Steigenberger and Montenbruck, 2024), which documents the use of specific PRNs or slot numbers by individual SVNs as a function of time. Furthermore, the frequency band (cf. Table 1) of the tracked signal must be identified. To facilitate translation, the numerical value of the ANTEX frequency band identifier (see Table 1) matches the band/frequency indicator in the central digit of the RINEX observation codes (Gini, 2024).
- Users of IGS satellite (transmit) antenna models are advised to pay proper attention to the '`ORIGIN`' parameter in the metadata of the antenna record. While current IGS antenna models still refer the phase center offset to the spacecraft center of mass, future models will transition to a fixed antenna reference point in the spacecraft body system (see Fig. 2) to better handle time-varying CoM locations. As such, users shall prepare to retrieve the CoM-to-ARP vector of GNSS satellites from information in the IGS satellite metadata SINEX file rather than relying on CoM-referenced antenna information.

Abbreviations

ANTEX	ANTenna EXchange format
ARF	Antenna Reference Frame
ARP	Antenna Reference Point
ASCII	American Standard Code for Information Interchange
BCR	Bottom of Chokering
CC	Code phase Center
CCO	Code phase Center Offset
CDMA	Code Division Multiple Access
CoM	Center of Mass
FDMA	Frequency Division Multiple Access
GDV	Group Delay Variation
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Global Navigation Satellite System)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IGS	International GNSS Service
LNA	Low-Noise Amplifier
NaN	Not a Number
NRP	North Reference Point
PC	Phase Center
PCO	Phase Center Offset
PPP	Precise Point Positioning
PRN	Pseudo-Random Noise
RINEX	Receiver INdependent EXchange format
RTCM	Radio Technical Commission for Maritime Services
SINEX	Solution INdependent EXchange format
SN	Serial Number
SVN	Space Vehicle Number
TCR	Top of Chokering
TRF	Terrestrial Reference Frame
TUM	Technical University Munich

References

Beer S, Wanninger L, Heßelbarth A (2021) Estimation of absolute GNSS satellite antenna group delay variations based on those of absolute receiver antenna group delays. GPS Solutions 25(3):110, DOI 10.1007/s10291-021-01137-8

Gini F (2024) RINEX, The Receiver Independent Exchange Format, Version 4.02. URL https://files.igs.org/pub/data/format/rinex_4.02.pdf

Hilla S (2016) The extended Standard Product 3 orbit format (SP3-d). URL https://files.igs.org/pub/data/format/sp3d.pdf

IGS (2025a) IGS naming conventions for GNSS equipment. URL https://files.igs.org/pub/station/general/rcvr_ant.tab

IGS (2025b) IGS satellite metadata file. URL https://files.igs.org/pub/station/general/igs_satellite_metadata.snx

IGS (2025c) Physical features of receiving antennas. URL https://files.igs.org/pub/station/general/antenna.gra

IGS (2025d) Transmit antenna names for GNSS satellites. URL https://files.igs.org/pub/station/general/satant.tab

Kersten T, Schön S (2017) GPS code phase variations (CPV) for GNSS receiver antennas and their effect on geodetic parameters and ambiguity resolution. Journal of Geodesy 91(6):579–596, DOI 10.1007/s00190-016-0984-8

Kouba J, Lahaye F, Tétreault P (2017) Precise point positioning. In: Teunissen P, Montenbruck O (eds) Springer Handbook of Global Navigation Satellite Systems, Springer, chap 19, pp 723–751, DOI 10.1007/978-3-319-42928-1_25

Mader G (1999) GPS antenna calibration at the National Geodetic Survey. GPS Solutions 3(1):50–58, DOI 10.1007/PL00012780

Menge F, Seeber G, Völksen C, Wübbena G, Schmitz M (1998) Results of absolute field calibration of GPS antenna PCV. In: ION GPS-98, pp 31–38

Misra P, Enge P (2011) Global Positioning System: Signals, Measurements, and Performance. Ganga-Jamuna Press

Montenbruck O, Schmid R, Mercier F, Steigenberger P, Noll C, Fatkulin R, Kogure S, Ganeshan AS (2015) GNSS satellite geometry and attitude models. Advances in Space Research 56(6):1015–1029, DOI 10.1016/j.asr.2015.06.019

Rao BR, Kunysz W, Fante R, McDonald K (2013) GPS/GNSS Antennas. Artech House

Rothacher M, Mader G (1996) Combination of antenna phase center offsets and variations. URL https://files.igs.org/pub/station/general/igs_01.txt

Rothacher M, Schmid R (2010) ANTEX: The antenna exchange format, version 1.4, 15 September 2010. URL https://files.igs.org/pub/data/format/antex14.txt

Schmid R, Steigenberger P, Gendt G, Ge M, Rothacher M (2007) Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas. Journal of Geodesy 81:781–798, DOI 10.1007/s00190-007-0148-y

Steigenberger P, Montenbruck O (2024) IGS satellite metadata file description. DOI 10.57677/metadata-sinex

Van Graas F, Bartone C, Arthur T (2004) GPS antenna phase and group delay corrections. In: Proc. ION NTM 2004, pp 399–408

Villiger A, Dach R, Schaer S, Prange L, Zimmermann F, Kuhlmann H, Wübbena G, Schmitz M, Beutler G, Jäggi A (2020) GNSS scale determination using calibrated receiver and galileo satellite antenna patterns. Journal of Geodesy 94(9):93, DOI 10.1007/s00190-020-01417-0

Wanninger L, Sumaya H, Beer S (2017) Group delay variations of GPS transmitting and receiving antennas. Journal of Geodesy 91(9):1099–1116, DOI 10.1007/s00190-017-1012-3

Wübbena G, Schmitz M, Warneke A (2019) Geo++ absolute multi-frequency GNSS antenna calibration. In: EUREF analysis center (AC) Workshop, p 2.01, URL https://epncb.oma.be/_newseventslinks/workshops/EPNLACWS_2019/pdf/2.01_gpp_cal125_euref19_p.pdf

Zeimetz P, Kuhlmann H (2008) On the accuracy of absolute GNSS antenna calibration and the conception of a new anechoic chamber. In: FIG Working Week 2008, URL https://www.gkgm.de/app/download/1375983/2008_zeimetz_kuhlmann.pdf