IONEX: The IONosphere Map EXchange Format Version 1

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Introduction

The International GPS Service for Geodynamics (IGS) provides precise GPS orbits, earth orientation parameters (EOPs), station coordinates, satellite clock information, and — on a test basis — tropospheric zenith delays. The IGS community is well aware of the fact that the IGS network can also be used to extract information about the total electron content (TEC) of the ionosphere on a global scale. One may expect that the IGS will include TEC maps into its product palette in the near future.

As part of the 1996 IGS Workshop in Silver Spring, a first effort has been made to compare GPS-derived TEC maps produced by IGS Analysis Centers (CODE and ESA/ESOC) as well as external processing centers (DLR Neustrelitz and University of New Brunswick) [Feltens, 1996a]. For this purpose, a very simple data exchange format proposed by Wilson (JPL) has been used.

One essential conclusion of the ionosphere-related discussion was that a common data format to exchange, compare, or combine TEC maps has to be defined. Based on a first format proposal by [Schaer, 1996], which strongly follows the Receiver INdependent EXchange format (RINEX) [Gurtner and Mader, 1990], [Schaer and Gurtner, 1996], and [Feltens, 1996b], we present a revised version of the so-called IONosphere map EXchange format (IONEX) that supports the exchange of 2- and 3-dimensional TEC maps given in a geographic grid.

The most important modifications with respect to [Schaer and Gurtner, 1996] are:

- Ionosphere maps given in an earth-fixed reference frame are supported only.
- Ionosphere maps are epoch-specific, i. e., they have to be interpreted as "snapshots" at certain epochs. Guidelines how to use IONEX TEC maps are formulated in the next section.
- In addition to TEC and RMS error maps, single-layer height maps are allowed, too.
- The option of 3-dimensional TEC maps has been included into IONEX, i. e., multi-layer models may be handled very easily by performing an additional loop over an equidistant height grid.
- TEC values are written using format `mI5` instead of `m(X1,I4)`. The definition of an exponent (see "`EXPONENT`") should help to cover the necessary dynamic range of electron density.
- Further satellite systems and techniques have been added to the list (see "`IONEX VERSION / TYPE`").
- A general escape sequence has been defined to include technique-related auxiliary data blocks in the header part of IONEX files.

Application of IONEX TEC Maps

We may use three different procedures to compute the TEC E as a function of *geocentric* latitude β, longitude λ, and universal time t, when we have the TEC maps $E_i = E(T_i), i = 1, 2, \ldots, n$ at our disposal:

- Simply take the nearest TEC map $E_i = E(T_i)$ at epoch T_i:

$$E(\beta, \lambda, t) = E_i(\beta, \lambda), \tag{1}$$

  where $|t - T_i| = \min$.

- Interpolate between consecutive TEC maps $E_i = E(T_i)$ and $E_{i+1} = E(T_{i+1})$:

$$E(\beta, \lambda, t) = \frac{T_{i+1} - t}{T_{i+1} - T_i}\, E_i(\beta, \lambda) + \frac{t - T_i}{T_{i+1} - T_i}\, E_{i+1}(\beta, \lambda), \tag{2}$$

  where $T_i \leq t < T_{i+1}$.

- Interpolate between consecutive *rotated* TEC maps:

$$E(\beta, \lambda, t) = \frac{T_{i+1} - t}{T_{i+1} - T_i}\, E_i(\beta, \lambda'_i) + \frac{t - T_i}{T_{i+1} - T_i}\, E_{i+1}(\beta, \lambda'_{i+1}), \tag{3}$$

  where $T_i \leq t < T_{i+1}$ and $\lambda'_i = \lambda + (t - T_i)$. The TEC maps are rotated by $t - T_i$ around the Z-axis in order to compensate to a great extent the strong correlation between the ionosphere and the Sun's position. Note that method (1) can be refined accordingly by taking the nearest *rotated* map: $E(\beta, \lambda, t) = E_i(\beta, \lambda')$.

From method (1) to method (3), one may expect an improvement of the interpolation results, therefore we recommend to use the last approach (3).

Grid interpolation algorithms to be used are not discussed in detail here. However, a simple 4-point formula should be adequate, if the IONEX grid is dense enough:

$$E(\lambda_0 + p\,\Delta\lambda, \beta_0 + q\,\Delta\beta) = (1-p)\,(1-q)\,E_{0,0} + p\,(1-q)\,E_{1,0} + q\,(1-p)\,E_{0,1} + p\,q\,E_{1,1},$$

where $0 \leq p < 1$ and $0 \leq q < 1$. $\Delta\lambda$ and $\Delta\beta$ denote the grid widths in longitude and latitude.

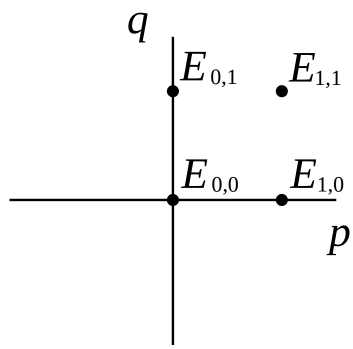

Figure 1: Bivariate interpolation using the nearest 4 TEC values $E_{i,j}$

General Format Description

Each IONEX file consists of a header section and a data section. The header section contains global information for the entire file and is placed at the beginning of the file. The header section contains header labels in columns 61–80 for each line contained in the header section. These labels are mandatory and must appear exactly as given in the IONEX descriptions. Note that the maximum record length is 80 bytes per record.

As record descriptors in columns 61–80 are mandatory, the programs reading an IONEX file should be able to decode the header records with formats according to the record descriptor, provided the records have been first read into an internal buffer.

We propose to allow free ordering of the header records, with the following exception:

- The "`IONEX VERSION / TYPE`" record must be the first record in a file.

There are further rules to be considered:

- Each value remains valid until changed by an additional header record!
- Fields of lines with formatted numbers must contain at least a "`0`" to facilitate reading with C language routines, i. e., empty fields are not permitted here.

- In principle there should be no blank lines. We recommend however to anticipate blank line skipping by the reading routines.

Writing and reading IONEX files one has to perform loops over up to a maximum of five arguments, namely: time (`EPOCH`), latitude (`LAT`), longitude (`LON`), height (`HGT`), and map type. Possible loops are:

(a) map type, `EPOCH`, `HGT`, `LAT`, `LON`,

(b) `EPOCH`, map type, `HGT`, `LAT`, `LON`.

Both enclosed examples have been created according to loop (a).

The proposed format descriptions as well as examples are given in the tables at the end of this paper.

Exchange of IONEX Files

We recommend to use the following naming convention for IONEX files:

`cccedddh.yyI`,

where

`ccc`:	3-figure Analysis Center (AC) designator
`e`:	extension or region code ("`G`" for Global ionosphere maps)
`ddd`:	day of the year of first record
`h`:	file sequence number $(1, 2, \ldots)$ or hour (`A`, `B`, ...) within day; 0: file contains all existing data of the current day
`yy`:	2-digit year
`I`:	file type ("`I`" for Ionosphere maps).

Example: `CODG2880.95I`. It is recommended to specify IONEX file names in uppercase.

When data transmission time or storage volume are critical we recommend to compress the files prior to storage or transmission using the UNIX compress und decompress programs. Compatible routines are available for VAX/VMS and PC/DOS systems.

Proposed naming conventions for compressed files:

System	Ionosphere files
UNIX	`cccedddh.yyI.Z`
VMS	`cccedddh.yyI_Z`
DOS	`cccedddh.yyJ`

Reading and Writing IONEX Modules

Fortran-77 routines to read and write IONEX files are available, for instance, via AIUB's anonymous ftp server `ubeclu.unibe.ch` (or `130.92.6.18`) — type "`cd aiub$ftp`" after login — in the directory `[IONEX.SOURCE]`. The main modules are `RDIXFL` (read IONEX file) and `WTIXFL` (write IONEX file). They use the subroutines `RDIXHD`/`WTIXHD` (read/write IONEX header) and `RDIXDT`/`WTIXDT` (read/write IONEX data). Auxiliary subroutines are: `DJUL` (date-to-MJD conversion), `JMT` (MJD-to-date conversion), and `RADGMS` (converts a day-fraction into hours-minutes-seconds). Note that the `OPNFIL`-`OPNERR` sequence must be replaced by an own file opening sequence.

References

Feltens, J. (1996a): *Ionosphere Maps — A New Product of IGS?* Summary of the Ionosphere Session, IGS Workshop, Silver Spring, MD, USA, March 19–21, 1996.

Feltens, J. (1996b): *IONEX Format.* GPS-IONO mail, October 30, 1996.

Gurtner, W., G. Mader (1990): *Receiver Independent Exchange Format Version 2.* CSTG GPS Bulletin, Vol. 3, No. 3, September/October 1990, National Geodetic Survey, Rockville.

Schaer, S. (1996): *Proposal Concerning VTEC Data Format.* GPS-IONO mail, February 6, 1996.

Schaer, S., W. Gurtner (1996): *IONEX: The IONosphere Map EXchange Format Version 0 (Proposal, August 1996).* GPS-IONO mail, September 3, 1996.

Appendix A: IONEX Version 1 Format Definitions and Examples

Table 1: Ionosphere map file — header section description

```
 +--------------------+------------------------------------------+------------+
 | HEADER LABEL       | DESCRIPTION                              | FORMAT     |
 | (Columns 61-80)    |                                          |            |
 +--------------------+------------------------------------------+------------+
 |IONEX VERSION / TYPE| o Format version (1.0)                   | F8.1,12X,  |
 |                    | o File type ('I' for Ionosphere maps)    | A1,19X,    |
 |                    | o Satellite system or theoretical model: | A3,17X     |
 |                    |   - 'BEN': BENt                          |            |
 |                    |   - 'ENV': ENVisat                       |            |
 |                    |   - 'ERS': ERS                           |            |
 |                    |   + 'GEO': GEOstationary satellite(s)    |            |
 |                    |   - 'GLO': GLOnass                       |            |
 |                    |   - 'GNS': GNSs (gps/glonass)            |            |
 |                    |   - 'GPS': GPS                           |            |
 |                    |   - 'IRI': IRI                           |            |
 |                    |   + 'MIX': MIXed/combined                |            |
 |                    |   - 'NNS': NNSs (transit)                |            |
 |                    |   - 'TOP': TOPex/poseidon                |            |
 |                    | This record has to be the first one in   |            |
 |                    | an IONEX file!                           |            |
 |                    | For techniques marked by a '+',          |            |
 |                    | description lines should be added        |            |
 |                    | identifying the satellite(s) or          |            |
 |                    | roughly specifying the technique used.   |            |
 +--------------------+------------------------------------------+------------+
 |PGM / RUN BY / DATE | o Name of program creating current file  | A20,       |
 |                    | o Name of agency  creating current file  | A20,       |
 |                    | o Date and time of file creation         | A20        |
 +--------------------+------------------------------------------+------------+
*|DESCRIPTION         | It is highly recommended to give a brief | A60        |*
 |                    | description of the technique, model, ... |            |
 |                    | Please distinguish between description   |            |
 |                    | and pure comment.                        |            |
 +--------------------+------------------------------------------+------------+
*|COMMENT             | Comment line(s). Note that comment lines | A60        |*
 |                    | are not allowed right at the beginning   |            |
 |                    | of a file or within TEC/RMS/HGT data     |            |
 |                    | blocks (see 'LAT/LON1/LON2/DLON/H').     |            |
 +--------------------+------------------------------------------+------------+
 |EPOCH OF FIRST MAP  | Epoch of first TEC map (UT):             | 6I6,24X    |
 |                    |   year (4 digits), month, day, hour,     |            |
 |                    |   min, sec (integer)                     |            |
 +--------------------+------------------------------------------+------------+
 |EPOCH OF LAST MAP   | Epoch of last TEC map (UT):              | 6I6,24X    |
 |                    |   year (4 digits), month, day, hour,     |            |
 |                    |   min, sec (integer)                     |            |
 +--------------------+------------------------------------------+------------+
 |INTERVAL            | Time interval between the TEC maps, in   | I6,54X     |
 |                    | seconds (integer). If '0' is specified,  |            |
 |                    | 'INTERVAL' may be variable.              |            |
 +--------------------+------------------------------------------+------------+
 |# OF MAPS IN FILE   | Total number of TEC/RMS/HGT maps         | I6,54X     |
```

```
 |                    | contained in current file.                 |            |
 +--------------------+--------------------------------------------+------------+
 |MAPPING FUNCTION    | Mapping function adopted for TEC deter-    | 2X,A4,54X  |
 |                    | mination:                                  |            |
 |                    |   'NONE': no MF used (e.g. altimetry),     |            |
 |                    |   'COSZ': 1/cos(z),                        |            |
 |                    |   'QFAC': Q-factor.                        |            |
 |                    | Others might be introduced.                |            |
 +--------------------+--------------------------------------------+------------+
 |ELEVATION CUTOFF    | Minimum elevation angle in degrees.        | F8.1,52X   |
 |                    | '0.0', if unknown; '90.0' for altimetry.   |            |
 +--------------------+--------------------------------------------+------------+
 |OBSERVABLES USED    | One-line specification of the observ-      | A60        |
 |                    | able(s) used in the TEC computation (or    |            |
 |                    | blank line for theoretical models).        |            |
 +--------------------+--------------------------------------------+------------+
*|# OF STATIONS       | Number of contributing stations.           | I6,54X     |*
 +--------------------+--------------------------------------------+------------+
*|# OF SATELLITES     | Number of contributing satellites.         | I6,54X     |*
 +--------------------+--------------------------------------------+------------+
 |BASE RADIUS         | Mean earth radius or bottom of height      | F8.1,52X   |
 |                    | grid (in km), e.g.: 6371 km or 6771 km.    |            |
 +--------------------+--------------------------------------------+------------+
 |MAP DIMENSION       | Dimension of TEC/RMS maps: 2 or 3.         | I6,54X     |
 |                    | See also 'TEC VALUES'.                     |            |
 +--------------------+--------------------------------------------+------------+
 |HGT1 / HGT2 / DHGT  | Definition of an equidistant grid in       | 2X,3F6.1,  |
 |                    | height:                                    | 40X        |
 |                    |   'HGT1' to 'HGT2' with increment 'DHGT'   |            |
 |                    |   (in km), e.g.: '   200.0 800.0  50.0'.   |            |
 |                    | For 2-dimensional maps, HGT1=HGT2 and      |            |
 |                    | DHGT=0, e.g.: '   400.0 400.0   0.0' or    |            |
 |                    |               '     0.0   0.0   0.0'       |            |
 |                    | (see also 'BASE RADIUS').                  |            |
 +--------------------+--------------------------------------------+------------+
 |LAT1 / LAT2 / DLAT  | Definition of the grid in latitude:        | 2X,3F6.1.  |
 |                    |   'LAT1' to 'LAT2' with increment 'DLAT'   | 40X        |
 |                    |   (in degrees).                            |            |
 |                    |   'LAT1' and 'LAT2' always have to be      |            |
 |                    |   multiples of 'DLAT'.                     |            |
 |                    |   Example: '    87.5 -87.5  -2.5'.         |            |
 +--------------------+--------------------------------------------+------------+
 |LON1 / LON2 / DLON  | Definition of the grid in longitude:       | 2X,3F6.1,  |
 |                    |   'LON1' to 'LON2' with increment 'DLON'   | 40X        |
 |                    |   (in degrees), where LON equals east      |            |
 |                    |   longitude.                               |            |
 |                    |   'LON1' and 'LON2' always have to be      |            |
 |                    |   multiples of 'DLON'.                     |            |
 |                    |   Example: '     0.0 357.5   2.5' or       |            |
 |                    |            '  -180.0 177.5   2.5'.         |            |
 +--------------------+--------------------------------------------+------------+
*|EXPONENT            | Exponent defining the unit of the values   | I6,54X     |*
 |                    | listed in the following data block(s).     |            |
 |                    | Default exponent is -1.                    |            |
 |                    | See also 'TEC VALUES', 'RMS VALUES', and   |            |
 |                    | 'HGT VALUES'.                              |            |
 +--------------------+--------------------------------------------+------------+
*|START OF AUX DATA   | Record opening general escape sequence     | A60        |*
```

```
 |                    | that contains technique-related          |            |
 |                    | auxiliary data (e.g. differential code   |            |
 |                    | biases for GPS).                         |            |
 |                    | Note that such data blocks may be        |            |
 |                    | skipped if you are interested in         |            |
 |                    | ionospheric information only.            |            |
 |                    | Format definitions and examples are      |            |
 |                    | given in Appendix B.                     |            |
 +--------------------+------------------------------------------+------------+
*|END OF AUX DATA     | Record closing auxiliary data block.     | A60        |*
 +--------------------+------------------------------------------+------------+
 |END OF HEADER       | Last record of the header section.       | 60X        |
 +--------------------+------------------------------------------+------------+
 |START OF TEC MAP    | Record indicating the start of the i-th  | I6,54X     |
 |                    | TEC map, where i=1,2,...,n denotes the   |            |
 |                    | internal number of the current map. All  |            |
 |                    | maps have to be ordered chronologically. |            |
 +--------------------+------------------------------------------+------------+
 |EPOCH OF CURRENT MAP| Epoch of current map (UT):               | 6I6,24X    |
 |                    |   year (4 digits), month, day, hour,     |            |
 |                    |   min, sec (integer).                    |            |
 |                    | 'EPOCH OF CURRENT MAP' must be specified |            |
 |                    | at the first occurrence of the           |            |
 |                    | associated map!                          |            |
 +--------------------+------------------------------------------+------------+
 |LAT/LON1/LON2/DLON/H| Record initializing a new TEC/RMS/HGT    | 2X,5F6.1,  |
 |                    | data block for latitude 'LAT' (and       | 28X        |
 |                    | height 'H(GT)'), from 'LON1' to 'LON2    |            |
 |                    | (with increment 'DLON').                 |            |
 |                    | In case of 2-dimensional maps, it is     !            |
 |                    | recommended to define H=HGT1.            |            |
 |                    | Neither other types of records nor       |            |
 |                    | comment lines are allowed after this     |            |
 |                    | record and within the subsequent data    |            |
 |                    | block!                                   |            |
 +--------------------+------------------------------------------+------------+
 |END OF TEC MAP      | Record indicating the end of the i-th    | I6,54X     |
 |                    | TEC map (see also 'START OF TEC MAP').   |            |
 +--------------------+------------------------------------------+------------+
*|START OF RMS MAP    | Record indicating the start of an RMS    | I6,54X     |*
 |                    | map related to the i-th TEC map (see     |            |
 |                    | also 'START OF TEC MAP').                |            |
 +--------------------+------------------------------------------+------------+
*|END OF RMS MAP      | Record indicating the end of an RMS map. | I6,54X     |*
 +--------------------+------------------------------------------+------------+
*|START OF HEIGHT MAP | Record indicating the start of a HEIGHT  | I6,54X     |*
 |                    | map related to the i-th TEC map (see     |            |
 |                    | also 'START OF TEC MAP').                |            |
 +--------------------+------------------------------------------+------------+
*|END OF HEIGHT MAP   | Record indicating the end of a HGT map.  | I6,54X     |*
 +--------------------+------------------------------------------+------------+
 |END OF FILE         | Last record closing the IONEX file.      | 60X        |
 +--------------------+------------------------------------------+------------+
```

(Records marked with "*" are optional)

Table 2: Ionosphere map file — data record description

```
 +-------------+--------------------------------------------------+------------+
 | OBS. RECORD | DESCRIPTION                                      | FORMAT     |
 +-------------+--------------------------------------------------+------------+
 | TEC VALUES  | TEC values in 0.1 TECU. After 16 values (per     | mI5        |
 |             | latitude band) continue values in next data      |            |
 |             | record. Non-available TEC values are written as  |            |
 |             | '9999'.                                          |            |
 |             | If an exponent k is specified, the TEC values    |            |
 |             | are given in units of 10**k TECU. The default    |            |
 |             | exponent is -1. See also 'EXPONENT'.             |            |
 |             | If 3-dimensional maps are provided, TEC values   |            |
 |             | should correspond to the surface electron        |            |
 |             | densities at the grid points times 'DHGT'        |            |
 |             | (again in 10**k TECU), that means, you can       |            |
 |             | derive the surface electron densities by simply  |            |
 |             | dividing the TEC values by 'DHGT'. However, if   |            |
 |             | you estimate electron densities integrated over  |            |
 |             | voxels (volume elements), you should ensure      |            |
 |             | that the height grid specified in 'HGT1 / HGT2   |            |
 |             | / DHGT' refers to the heights of the voxel       |            |
 |             | centers.                                         |            |
 +-------------+--------------------------------------------------+------------+
*| RMS VALUES  | RMS values are formatted exactly in the same     | mI5        |*
 |             | way as TEC values (see above).                   |            |
 +-------------+--------------------------------------------------+------------+
*| HGT VALUES  | HGT values are formatted exactly in the same     | mI5        |*
 |             | way as TEC values (see above).                   |            |
 |             | If an exponent k is specified, the HGT values    |            |
 |             | are given in units of 10**k km. The default      |            |
 |             | exponent is -1, too, i.e. in this case the unit  |            |
 |             | corresponds to 0.1 km.                           |            |
 |             | The actual heights (with respect to the 'BASE    |            |
 |             | RADIUS') are computed as the sum of 'HGT1' and   |            |
 |             | 'HGT VALUES'.                                    |            |
 +-------------+--------------------------------------------------+------------+
```

(Records marked with "*" are optional)

Table 3: Ionosphere map file — example 1: 2-d TEC maps

```
----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|

     1.0            IONOSPHERE MAPS     GPS                 IONEX VERSION / TYPE
ionpgm v1.0         aiub                29-jan-96 17:29     PGM / RUN BY / DATE
example of an ionex file containing 2-dimensional tec maps  COMMENT
global ionosphere maps for day 288, 1995                    DESCRIPTION
modeled by spherical harmonics ...                          DESCRIPTION
  1995    10    15     0     0     0                        EPOCH OF FIRST MAP
  1995    10    16     0     0     0                        EPOCH OF LAST MAP
 21600                                                      INTERVAL
     5                                                      # OF MAPS IN FILE
```

```
  COSZ                                                        MAPPING FUNCTION
    20.0                                                      ELEVATION CUTOFF
double-difference carrier phase                               OBSERVABLES USED
    80                                                        # OF STATIONS
    24                                                        # OF SATELLITES
  6371.0                                                      BASE RADIUS
     2                                                        MAP DIMENSION
   400.0 400.0   0.0                                          HGT1 / HGT2 / DHGT
    85.0 -85.0  -5.0                                          LAT1 / LAT2 / DLAT
     0.0 355.0   5.0                                          LON1 / LON2 / DLON
    -1                                                        EXPONENT
tec values in 0.1 tec units; 9999, if no value available      COMMENT
height values in 0.1 km                                       COMMENT
                                                              END OF HEADER
     1                                                        START OF TEC MAP
  1995    10    15     0     0     0                          EPOCH OF CURRENT MAP
    85.0   0.0 355.0   5.0 400.0                              LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
    80.0   0.0 355.0   5.0 400.0                              LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
   -85.0   0.0 355.0   5.0 400.0                              LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
     1                                                        END OF TEC MAP
     2                                                        START OF TEC MAP
  1995    10    15     6     0     0                          EPOCH OF CURRENT MAP
    85.0   0.0 355.0   5.0 400.0                              LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
     5                                                        END OF TEC MAP
     1                                                        START OF RMS MAP
    85.0   0.0 355.0   5.0 400.0                              LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
    80.0   0.0 355.0   5.0 400.0                              LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
```

```
 1000 1000 1000 1000 1000 1000 1000 1000
...
   -85.0   0.0 355.0   5.0 400.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
     1                                                      END OF RMS MAP
     2                                                      START OF RMS MAP
    85.0   0.0 355.0   5.0 400.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
     5                                                      END OF RMS MAP
     1                                                      START OF HEIGHT MAP
    85.0   0.0 355.0   5.0 400.0                            LAT/LON1/LON2/DLON/H
    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    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    0    0    0    0
    0    0    0    0    0    0    0    0
    80.0   0.0 355.0   5.0 400.0                            LAT/LON1/LON2/DLON/H
    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    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    0    0    0    0
    0    0    0    0    0    0    0    0
...
   -85.0   0.0 355.0   5.0 400.0                            LAT/LON1/LON2/DLON/H
    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    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    0    0    0    0
    0    0    0    0    0    0    0    0
     1                                                      END OF HEIGHT MAP
     2                                                      START OF HEIGHT MAP
    85.0   0.0 355.0   5.0 400.0                            LAT/LON1/LON2/DLON/H
    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    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    0    0    0    0
    0    0    0    0    0    0    0    0
...
     5                                                      END OF HEIGHT MAP
                                                            END OF FILE

----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|
```

Table 4: Ionosphere map file — example 2: 3-d TEC maps

```
----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|

     1.0            IONOSPHERE MAPS     GPS                 IONEX VERSION / TYPE
ionpgm v1.0         aiub                29-jan-96 17:29     PGM / RUN BY / DATE
example of an ionex file containing 3-dimensional tec maps  COMMENT
global ionosphere maps for day 288, 1995                    DESCRIPTION
modeled by spherical harmonics ...                          DESCRIPTION
  1995    10    15     0     0     0                        EPOCH OF FIRST MAP
  1995    10    16     0     0     0                        EPOCH OF LAST MAP
 21600                                                      INTERVAL
     5                                                      # OF MAPS IN FILE
  COSZ                                                      MAPPING FUNCTION
    20.0                                                    ELEVATION CUTOFF
double-difference carrier phase                             OBSERVABLES USED
    80                                                      # OF STATIONS
    24                                                      # OF SATELLITES
  6371.0                                                    BASE RADIUS
     3                                                      MAP DIMENSION
   200.0 800.0  50.0                                        HGT1 / HGT2 / DHGT
    85.0 -85.0  -5.0                                        LAT1 / LAT2 / DLAT
     0.0 355.0   5.0                                        LON1 / LON2 / DLON
                                                            END OF HEADER
     1                                                      START OF TEC MAP
  1995    10    15     0     0     0                        EPOCH OF CURRENT MAP
    -3                                                      EXPONENT
    85.0   0.0 355.0   5.0 200.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
    80.0   0.0 355.0   5.0 200.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
   -85.0   0.0 355.0   5.0 200.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
    -2                                                      EXPONENT
    85.0   0.0 355.0   5.0 250.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
    80.0   0.0 355.0   5.0 250.0                            LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
```

```
 1000 1000 1000 1000 1000 1000 1000 1000
...
   -85.0   0.0 355.0   5.0 250.0                           LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
    -4                                                          EXPONENT
    85.0   0.0 355.0   5.0 800.0                           LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
    80.0   0.0 355.0   5.0 800.0                           LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
   -85.0   0.0 355.0   5.0 800.0                           LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
     1                                                          END OF TEC MAP
     2                                                          START OF TEC MAP
  1995    10    15     6     0     0                          EPOCH OF CURRENT MAP
    -3                                                          EXPONENT
    85.0   0.0 355.0   5.0 200.0                           LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
     5                                                          END OF TEC MAP
     1                                                          START OF RMS MAP
    -3                                                          EXPONENT
    85.0   0.0 355.0   5.0 200.0                           LAT/LON1/LON2/DLON/H
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
 1000 1000 1000 1000 1000 1000 1000 1000
...
     5                                                          END OF RMS MAP
                                                                END OF FILE

----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|
```

Appendix B: Auxiliary Data Blocks

GPS/GLONASS-Related Data Block

If single-frequency GPS users apply precise ephemerides and precise satellite clock information — which always refers to the ionosphere-free linear combination (LC) — as well as IONEX TEC maps to eliminate or greatly reduce ionosphere-induced errors, they may also be interested in having a set of differential code biases (DCBs) of the satellites to correct their C/A- or P1-code measurements accordingly (to make them consistent to the LC satellite clocks — or vice versa). The DCBs b are estimated simultaneously with the TEC parameters using the relationship

$$c\,b = (\mathrm{P1} - \mathrm{P2})_{\mathrm{observed}} - (\mathrm{P1} - \mathrm{P2})_{\mathrm{corrected}},$$

where P1 and P2 denote the C/A- or P-code observables in meters on L1 (under AS or non-AS conditions) and L2, respectively. The DCB correction for the P1 measurements *or* for the LC satellite clock values T_{LC} (from SP3 orbit file) are given by

$$\mathrm{P1}_{\mathrm{corrected}} = \mathrm{P1}_{\mathrm{observed}} - \kappa_2\,c\,b$$

and

$$T_{\mathrm{corrected}} = T_{\mathrm{LC}} + \kappa_2\,b,$$

where $\kappa_2 = -\nu_2^2/(\nu_1^2 - \nu_2^2) = -1.55$ is the second LC factor, ν_i is the frequency of the i-th carrier, c is the vacuum speed of light, and $b = b_1 - b_2$ is the (geometry-free) DCB of the SV considered (usually in nanoseconds).

Since the DCB information is a by-product of the TEC determination when analyzing dual-band code measurements, DCB estimates may be included in IONEX files. The *GPS/GLONASS*-related data block has to be labelled with "`DIFFERENTIAL CODE BIASES`" (see example in Table 2).

Table 1: Differential code biases — format definitions

HEADER LABEL (Columns 61-80)	DESCRIPTION	FORMAT
PRN / BIAS / RMS	Pseudo Random Number (PRN), differential (L1-L2) code bias, and its RMS error in nanoseconds. Note that the PRN consists of a character indicating the satellite system ('G' or blank for GPS and 'R' for GLONASS) and the actual PRN (2 digits).	3X,A1,I2.2, 2F10.3,34X
*COMMENT	Comment lines are allowed.	A60 *

(Records marked with "*" are optional)

Table 2: Differential code biases — example

```
----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|

DIFFERENTIAL CODE BIASES                                    START OF AUX DATA
    01     0.000     0.000                                  PRN / BIAS / RMS
    02     0.000     0.000                                  PRN / BIAS / RMS
...
    31     0.000     0.000                                  PRN / BIAS / RMS
l1-l2 biases and rms in ns                                  COMMENT
sum of biases constrained to zero                           COMMENT
DIFFERENTIAL CODE BIASES                                    END OF AUX DATA

----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|
```