How to use CODE's Global Ionosphere Maps

Stefan Schaer
Astronomical Institute, University of Berne
sschaer@aiub.unibe.ch

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Indroduction

The *Center for Orbit Determination in Europe (CODE)* — one of the Analysis Centers of the *International GPS Service for Geodynamics (IGS)* — provides precise GPS orbits, Earth orientation parameters, station coordinates, and other parameters of geophysical interest on a daily basis using the *ionosphere-free* linear combination of doubly differenced GPS carrier phase observations.

Since January 1, 1996, *Global Ionosphere Maps (GIMs)* are routinely estimated as an additional product by analyzing the so-called *geometry-free* linear combination which contains the information on ionospheric refraction. The *Total Electron Content (TEC)* is developed into a series of spherical harmonics adopting a single-layer model in a Sun-fixed reference frame. For each day a set of TEC coefficients is determined which approximates an average distribution of the vertical TEC on a global scale. The GIMs produced are already used in the CODE processing to improve the resolution of the initial carrier phase ambiguities [Rothacher et al., 1996a].

GIM files containing the GPS-derived TEC coefficients are made available through anonymous ftp. Users of the Bernese GPS Software Version 4.0 can directly apply CODE's GIM files in their GPS data processing [Rothacher et al., 1996b]. Spaceborne applications (e. g. altimetry) may benefit from these rapidly available TEC maps as well. For ionosphere physicists these maps are an alternative source of information about the *deterministic* behaviour of the ionosphere, that may be correlated with solar and geomagnetic indices and compared to theoretical ionosphere models.

TEC Mapping Technique

At present (May 1997), the CODE Analysis Center is processing the data of 84 globally distributed stations of the world-wide GPS tracking network of the IGS. Figure 1 shows the stations used by CODE. Dashed "circles" indicate those regions where the ionosphere is probed. The diameter of such an area is about 2 000 kilometers when using an elevation cut-off angle of 20 degrees.

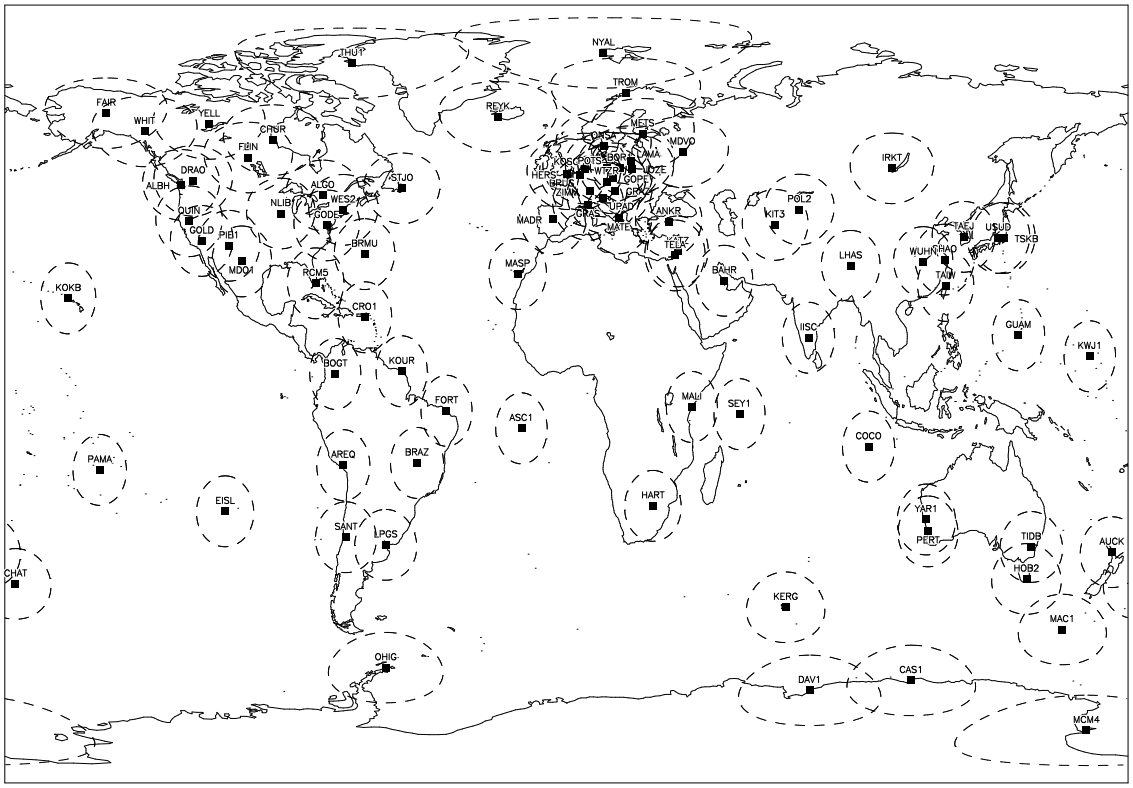

Figure 1: IGS stations currently used by CODE

CODE GIMs are based on the so-called *single-layer* or *thin-shell* model which is outlined in Figure 2. This model assumes that all free electrons are concentrated in a spherical shell of infinitesimal thickness. The conversion from *vertical* TEC E_{V} into *slant* TEC E is written as

$$E = F(z)\, E_{\mathrm{V}} = \frac{1}{\cos z'}\, E_{\mathrm{V}} \qquad \text{with} \quad \sin z' = \frac{R}{R_0 + H}\, \sin z, \tag{1}$$

where

$F(z) = 1/\cos z'$ denotes the *single-layer* mapping function,

z, z' are the (geocentric) zenith distances at the height of the station and the single-layer, respectively (see Figure 2),

R is the radius with respect to the station considered,

$R_0 = 6371$ km is the mean radius of the Earth, and

H is the height of the single-layer above the Earth's mean surface.

The height H of this idealized layer is usually set to the height of the expected maximum electron density: e. g. $H = 400$ km.

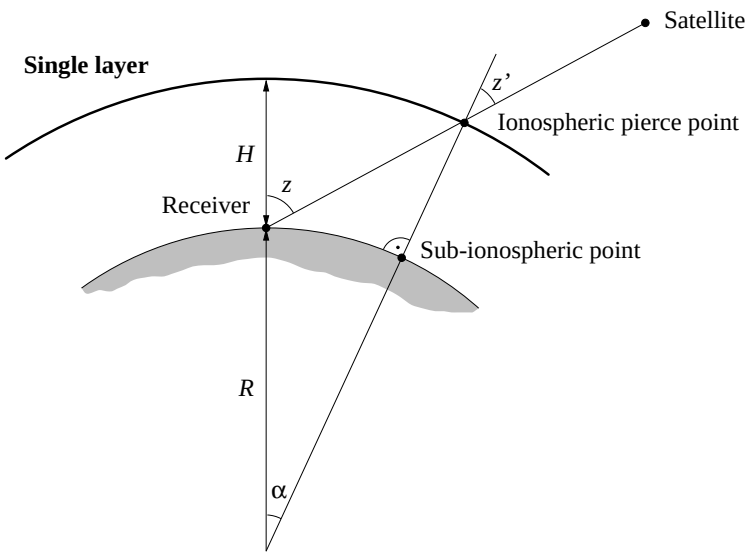

Figure 2: Single-layer model

We model the electron density E — the surface density of the layer — representing the TEC distribution on a global scale as

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \widetilde{P}_{nm}(\sin\beta)\,(a_{nm}\,\cos ms + b_{nm}\,\sin ms), \tag{2}$$

where

E is the (vertical) Total Electron Content (TEC),

β is the geocentric latitude of the intersection point of the line receiver–satellite with the ionospheric layer,

$s = \lambda - \lambda_0$ is the *Sun*-fixed longitude of the ionospheric pierce point — or sub-ionospheric point (see Figure 2), i. e. the difference between the *Earth*-fixed longitude λ and the longitude of the Sun λ_0,

$n_{\max}$ is the maximum degree of the spherical harmonic expansion,

$\widetilde{P}_{nm} = \Lambda_{nm}\,P_{nm}$ are the *normalized* associated Legendre functions of degree n and order m based on the normalization factor Λ_{nm} and the classical (unnormalized) Legendre functions P_{nm}, and

a_{nm}, b_{nm} are the TEC coefficients of the spherical functions, i. e. the GIM parameters describing the global TEC.

The TEC $E(\beta, s)$ is given in TEC Units (TECU), where 1 TECU corresponds to 10^{16} free electrons per square meter. For the coordinates (β, s), we may use an equivalent set in the solar-*geomagnetic* frame as well. If the Sun-fixed reference frame is referred to the "mean" Sun, the *geographic* longitude of the Sun may be written as

$$\lambda_0 = \pi - \mathrm{UT}, \tag{3}$$

where UT is the Universal Time (in radians); the Sun's geographic latitude β_0 is set to 0.

The normalization factor Λ_{nm} is defined as

$$\Lambda_{nm} = \sqrt{\frac{(n-m)!\,(2n+1)\,(2-\delta_{0m})}{(n+m)!}}, \tag{4}$$

where δ denotes the Kronecker delta.

Note that the TEC representation (2) does *not* provide a model for the time dependence in the *Sun*-fixed reference frame because the "frozen" TEC structure is co-rotating with the Sun. However, there is always a time dependence in the *Earth*-fixed frame. Further information concerning global (and regional) ionosphere modeling may be found in [Schaer et al., 1995], [Schaer et al., 1996a], as well as in [Rothacher et al., 1996b].

The Global Ionosphere Maps — or "Models" — (GIMs) routinely produced by the CODE Analysis Center [Schaer et al., 1996a]

- refer to the solar-*geographical* reference frame that is coupled with the "mean" Sun, i. e. taking into account equation (3) the argument s may simply be computed as $s = \lambda + \mathrm{UT} - \pi$,
- cover a time span of 24 hours (from 0 to 24 UT),
- are complete up to degree/order 8, i. e. each individual GIM is described by 81 TEC coefficients.

Availability of GIM Files

GIMs are estimated on a daily basis. GIM files containing the GPS-derived TEC coefficients are made available — with a delay of about 4 days — via our *anonymous* ftp server `ubeclu.unibe.ch`[1] (`130.92.6.10`). CODE GIM files are named `CODwwwwd.ION`, where `wwww` denotes the GPS week (e. g. 0844) and `d` is the week day number (starting on Sunday with `d` = 0). GIM files of the current year are stored in the directory `[CODE]`; older ones starting with January 1, 1995 are saved in directories `[CODE.yyyy]`, where `yyyy` denotes the 4-digit year (e. g. 1995). You may get access to all `ION` files of the current year as follows:

[1] Type "`cd aiub$ftp`" after login!

```
ftp ubeclu.unibe.ch
anonymous
(your complete e-mail address)
cd aiub$ftp
cd code
```

Tables that allow the conversion of dates between different notations are given in the files `[DIVERS]CALENDAR.Yyy`, where `yy` represents the 2-digit year (e. g. 96).

An example of an `ION` file is listed in Figure 3. The corresponding file `COD08443.ION` covering day 73 (or March 13), 1996 is also stored in the directory `[IONOSPHERE.DOC]`. This document here is available as PS file in this directory, too: `[IONOSPHERE.DOC]GIMMAN.PS`. Furthermore, the papers [Schaer et al., 1995] and [Schaer et al., 1996a] are contained in the PS files `IONPAP95.PS` and `IONPAP96.PS`, directory `[PAPERS]`.

```
CODE: GLOBAL IONOSPHERE MODEL FOR DAY 073, 1996                  17-MAR-96 04:30
--------------------------------------------------------------------------------
IONOSPHERE MODEL NUMBER                          : 0731-00
TYPE OF IONOSPHERE MODEL (1=LOCAL,2=GLOBAL)      :    2
MAXIMUM DEGREE OF SPHERICAL HARMONICS            :    8
MAXIMUM ORDER                                    :    8
DEVELOPMENT WITH RESPECT TO
  GEOGRAPHICAL (=1) OR GEOMAGNETIC (=2) FRAME    :    1
  MEAN (=1) OR TRUE (=2) POSITION OF THE SUN     :    1
MAPPING FUNCTION (1=1/COS)                       :    1
HEIGHT OF SINGLE LAYER AND ITS RMS ERROR (KM)    :  400.00     0.00
COORDINATES OF EARTH-CENTERED DIPOLE AXIS
  LATITUDE OF NORTH GEOMAGNETIC POLE (DEGREES)   :
  EAST LONGITUDE (DEGREES)                       :
PERIOD OF VALIDITY
  FROM EPOCH / REFERENCE EPOCH (Y,M,D,H,M,S)     : 1996 03 13 00 00 00
  TO EPOCH                                       : 1996 03 13 23 59 59
LATITUDE BAND COVERED
  MINIMUM LATITUDE (DEGREES)                     :  -85.75
  MAXIMUM LATITUDE (DEGREES)                     :   87.09
ADDITIONAL INFORMATION
  NUMBER OF CONTRIBUTING STATIONS                :   64
  TID INDICATOR (TECU)                           :    0.99
COMMENT / WARNING                                :
COEFFICIENTS
DEGREE  ORDER    VALUE (TECU)   RMS (TECU)
   0       0       10.66643935     0.0322
   1       0       -0.98758858     0.0310
   1       1        4.64559206     0.0307
   .       .        .              .
   .       .        .              .
   .       .        .              .
   8      -8        0.06239174     0.0105
```

Figure 3: GIM file `COD08443.ION`

Currently discussions about common TEC data standards are under way within the *International GPS Service for Geodynamics (IGS)* (see e. g. [Schaer et al., 1997][2]). We expect that the IGS community will agree on a software-independent TEC data exchange format in order to easily exchange, compare, and eventually combine TEC maps in the future.

[2]The corresponding PS file can be found in `[IONEX]IONEX1.PS`.

A contour plot of a CODE GIM given in the solar-geographical coordinate system is shown in Figure 4. Note that the header part of the associated `ION` file was shown in Figure 3. The latitude range covered $(-85.75^\circ, +87.09^\circ)$ is indicated by two dashed lines.

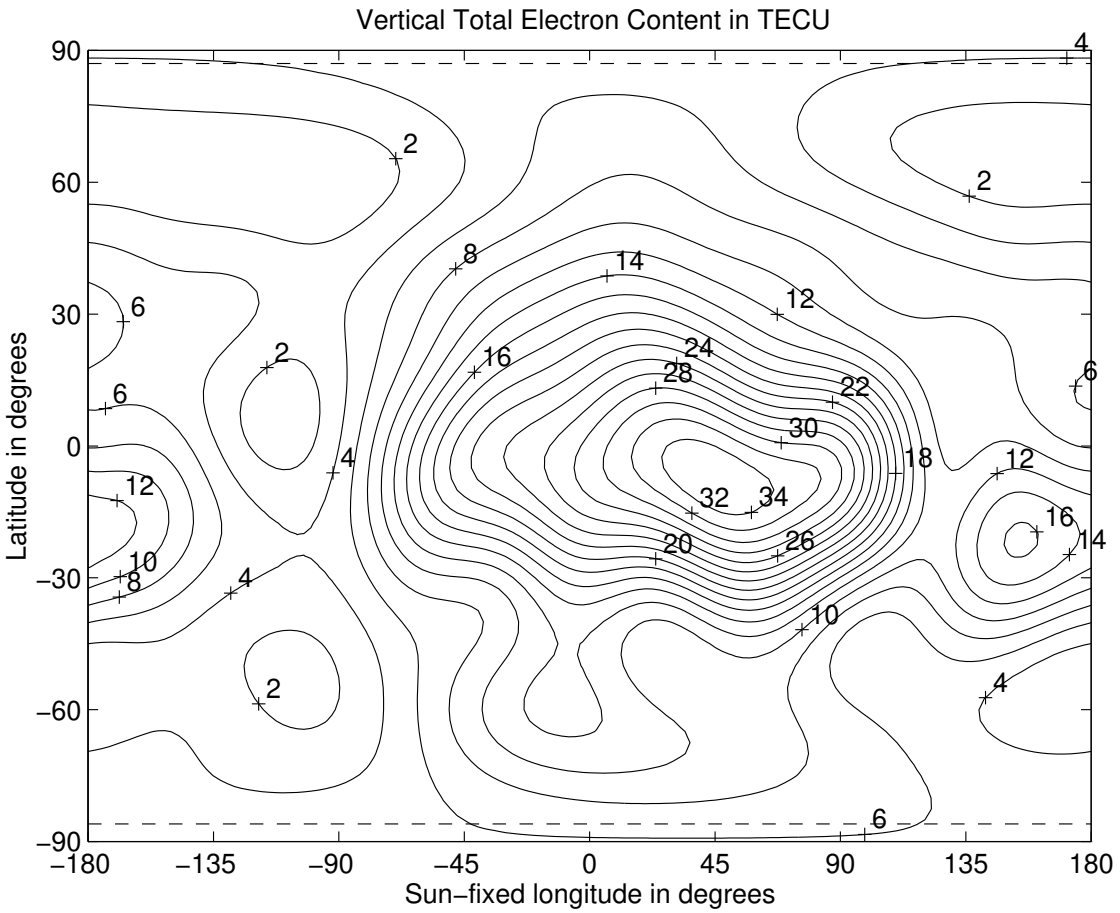

Figure 4: Global Ionosphere Map (GIM) for day 073, 1996

You may use the above TEC map to verify your own software implementation. We also list two special TEC values, namely the maximum and minimum TEC:

$$E_{\max}(\beta, s) = E(-7.60^\circ, +45.37^\circ) = 35.79\,\text{TECU}$$
$$E_{\min}(\beta, s) = E(+60.91^\circ, -106.64^\circ) = 0.34\,\text{TECU}$$

Figure 5 finally shows the *mean* TEC[3] — extracted from the one-day GIMs — that roughly describes the evolution of the ionospheric activity on a global scale.

[3]The *mean* TEC corresponds to the zero-degree TEC coefficient a_{00}.

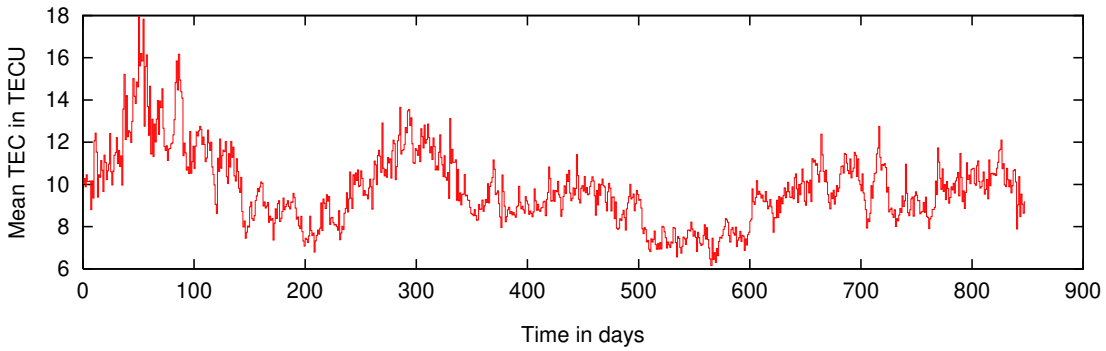

Figure 5: 28-month GIM statistics from January 1, 1995 to April 26, 1997

Rapid GIMs

Since July 1, 1996, a *rapid* product is created as part of the rapid-orbit generation procedure. These rapid GIMs are based on *fewer* contributing GPS stations than usually available for the final product but they are available with a delay of 12 hours only. If the rapid GIM covers a minimum latitude range of ±45 degrees, it is made available via anonymous ftp under `CODwwwwd.ION_R`.

Regional Ionosphere Maps

Since December 1995, we also generate regional ionosphere maps for Europe based on about 30 European IGS stations in a fully automatic mode [Rothacher et al., 1996a]. These ionosphere maps are used in the processing scheme of the European cluster solution to support the ambiguity resolution there. European TEC map files are made available with a delay of 11 days under `[BSWUSER.ATM]EURyyddd.ION`, where `yy` is the 2-digit year and `ddd` is the doy. The principles to use the regional ionosphere maps remain the same except that the TEC is applicable only within a well-defined latitude and longitude range [Schaer et al., 1995].

Short Description of Important Subroutines

The source code of GIM-specific subroutines of the *Bernese GPS Software* [Rothacher et al., 1996b] may be copied from the anonymous-ftp directory `[IONOSPHERE.FOR]`.

Let us briefly explain these Fortran-77 subroutines focusing on the essential features:

`GETGIM`: This subroutine reads `ION` files and therefore the format statements are of major importance. There are a lot of checks which might be skipped. `GETGIM` has been

designed to handle multi-session GIMs as well. However, for one-day models, you have the case with `NMODEL` = 1 only. The conversion of time arguments into modified Julian date is done by `DJUL`.

`ASLEFU`: `ASLEFU` — derived from ASsociated LEgendre FUnctions — is a routine to compute the spherical functions needed. This subroutine can be completely taken over without any modification — including the function `FAKULT` that evaluates factorials.

`GIMARG`: The subroutine `GIMARG` (GIM ARGuments) computes the coordinates (β, s) of the intersection point of the line satellite–receiver with the ionospheric layer as well as the mapping factor $F(z)$:

```
FACSLM(1)=FACGIM(ICARR)/DCOS(ZEN2)
```

`ZEN2` corresponds to z'. Note that the constant `CONRE` equals $R_0 = 6371\,\mathrm{km}$. Reducing altimeter data, `GIMARG` is not as important, because you then deal with nadir measurements only, i. e. $z' = 0$ and thus $F(z) = 1$. If you process non-GPS data, you have to adjust the frequency of the radio signal analyzed (see variables `FACTEC`, `FREQ`, and `FACGIM(ICARR)`). When handling GIMs that refer to a solar-geomagnetic coordinate system, we use the subroutines `DDREH` and `DMLMAV` to perform the coordinate transformation.

`IONOSP`: In this subroutine the ionospheric distance correction is computed. An essential part is the computation of the double sum according to TEC representation (2):

```
            DO 240 ITERM=1,NTERM(IM)
              IDEG=NM(ITERM,1,IM)
              IORD=NM(ITERM,2,IM)
              IF (IM.EQ.IM1) THEN
                ESUM=ESUM+FAC1*IONCOE(ITERM,IM)*
     1            ASLEFU(XLAT,XSFL,IDEG,IORD,1)
              ELSE
                ESUM=ESUM+FAC2*IONCOE(ITERM,IM)*
     1            ASLEFU(XLAT,XSFL,IDEG,IORD,1)
              END IF
240         CONTINUE
```

`ESUM` corresponds to the *vertical* TEC $E(\beta, s)$. The actual distance correction `DR` (in meters) is computed in the following line:

```
DR=FACSLM(1)*ESUM
```

General Remark

The GIMs produced by CODE are freely available. We are very much interested in your experiences with our models. Furthermore we would appreciate it if you could reference the use of our models.

References

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