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IFMS Ranging Processing and Calibration Software: Level 1a to Level 2
Software Design Specifications

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ACRONYMS

A/D	Analog/Digital
AGC	Automatic Gain Control
AGVTP	Archive Generation, Validation and Transfer Plan
AOL	Amplitude Open Loop
ATDF	Archival Tracking Data Format
CD-ROM	Compact Disk - Read Only Memory
CL	Closed-Loop
DDS	Data Delivery System
DSN	Deep Space Network
DVD	Digital Versatile Disk
ESA	European Space Agency
ESOC	European Space Operation Center
ESTEC	European Space Technology Center
FOL	Frequency Open Loop
G/S	Ground Station
HGA	High Gain Antenna
IFMS	Intermediate Frequency Modulation System
JPL	Jet Propulsion Laboratory
LCP	Left Circular Polarization
LGA	Low Gain Antenna
LOS	Line Of Sight
MaRS	Mars Express Radio Science Experiment
MGA	Medium Gain Antenna
MGS	Mars Global Surveyor
NASA	National Aeronautics and Space Administration
ODR	Original Data Record
OL	Open-Loop
ONED	one-way dual-frequency mode
ONES	One-way single-frequency mode
PDS	Planetary Data System
POL	Polarization Open Loop
RCP	Right Circular Polarization
RSR	Radio Science Receiver
RX	Receiver
S/C	Spacecraft
SIS	Software Interface Specification
S-TX	S-Band Transmitter
SPICE	Space Planet Instrument C-Matrix Events

TBC	To Be Confirmed
TBD	To Be Determined
TWOD	Two-way dual-frequency mode
TWOS	Two-way single-frequency mode
USO	Ultra Stable Oszillator
X-TX	X-band Transmitter

Contents

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1 INTRODUCTION

1.1 SCOPE

This document specifies the requirements for the development of the IFMS ranging processing software, transferring Level 1a IFMS range data towards Level 2. The software shall analyze radio ranging tracking data, recorded at the IFMS receiving systems of the ground stations New Norcia (NNO). AGC and meteo data are handeled via the IFMS labeling software.

1.2 REFERENCED DOCUMENTS

	Reference Number	Title	Issue Number	Date
[1]	MEX-MRS-IGM-IS-3016	Radio Science File naming Convention	5.1	17.07.2003
[2]	IFMS_OCCFTP_10_3_1.PDF	IFMS-to-OCC	9.3	
[3]	M32ESOCL1B_RCL_030522_00.PDF	MEX transponder Group delay values	1.0	17.02.2003
[4]	VEX-VERA-UBW-TN-3040	Reference Systems and Techniques Used for the Simulation and Prediction of Atmospheric and Ionospheric Sounding Measurements at Planet Venus	3.2	12.11.2003

1.3 DOCUMENT OVERVIEW

Section 2 defines the design specifications of the main program
Section 3 defines the specifications of the subroutines.

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2 MAIN PROGRAM SPECIFICATIONS

The software shall read the IFMS level 1a range data either at S-band or X-band depending on the used uplink frequency band, and computes from the delay the RTLT. The RTLT will be calibrated and range residuals will be computed using the predicted RTLT from subroutine PREDICT.

2.1 MODULES

The MAIN program consists of a number of modules:

1. M_READ_INPUT_DATA
2. M_PREDICT
3. M_GOLBAL_VAR
4. M_RTLT
5. M_OUTPUT
6. M_CALIBRATION with M_IONO_CAL
7. M_RANGE_CALC
8. M_RANGE_OUTPUT

and a lot of utility modules:

9. M_WIN_UTILITY
10. M_INTERPOL
11. M_SEARCH
12. M_FILE_MOD
13. M_FILE_UTILITIES
14. M_ERROR
15. M_READ_HEADER
16. M_LABEL
17. M_LableNameIFMS
18. M_FileNamingConvention
19. M_SPICE

The flow diagram is shown in section 2.1.4.

2.2 INPUT FILES

2.2.1 Data file types

IFMS-SPEC-2210: the following table defines the input file types and the logical file names used in this specification and within the program:

File type	Logical name within program
IFMS level 1a range X-band	IFMS_RANGE
SPICE Kernels	SPICE_MEX_S/C SPICE_NNO_G/S
Range calibration file	IFMS_RANGE_CAL
Transponder calibration table	TRANSPONDER_CAL Defined in IFMS-DEF-1040
Geometric G/S calibration	GS_GEO_CAL Defined in IFMS-DEF-1050
IFMS_Meteo file level 1b	IFMS_METEO
IFMS AGC file level 1b	IFMS_AGC
Klobuchar coefficients for Earth ionosphere calibration	ION_COEFF

2.2.2 File names

IFMS-SPEC-2220: File names of IFMS_RANGE are defined in [2] and in [1] section 5.2

IFMS-SPEC-2221: File names of RANGE_CAL, IFMS_METEO, IFMS_AGC are defined in [1] section 4.1

IFMS-SPEC-2222: File names of the SPICE kernels are defined in [1] section 11.

2.2.3 File formats

IFMS-SPEC-2230: File formats are defined in [2], in [1] in section 5.2, section 8 and section 9

2.3 DEFINITION OF CONSTANTS

IFMS-DEF-1010: ASTRONOMICAL UNIT (AU)

1 AU = 149,597,870 kilometers

IFMS-DEF-1020: SPEED OF LIGHT

c = 299,792,458 m/s

IFMS-DEF-1030: CARRIER FREQUENCIES Mars Express

Mars Express:

frequency band	uplink	downlink
S-band	2114.676 MHz	2296.482 MHz
X-band	7116.936 MHz	8420.432 MHz

IFMS-DEF-1031: Transponder coherency constants and ratios

Mars Express:

frequency band uplink	transponder ratios downlink/uplink	
	S-band	**X-band**
S-band	240/211	880/211
X-band	240/749	880/749

IFMS-DEF-1040: Transponder group delay values [3]. See also Annex A (4.1).
This is defined as Table TRANSPONDER_CAL

Mars Express

Transponder 1: at 25°C Temperature

frequency band uplink	**transponder range delay (nanoseconds)**	
	S-band	**X-band**
S-band	2025	2013
X-band	2018	2010

Transponder 2:

frequency band uplink	**transponder range delay (nanoseconds)**	
	S-band	**X-band**
S-band	2032	2015
X-band	2025	2015

IFMS-DEF-1050: Ground station geometric calibration
This is defined as GS_GEO_CAL
These values have to be substracted from the measured calibration

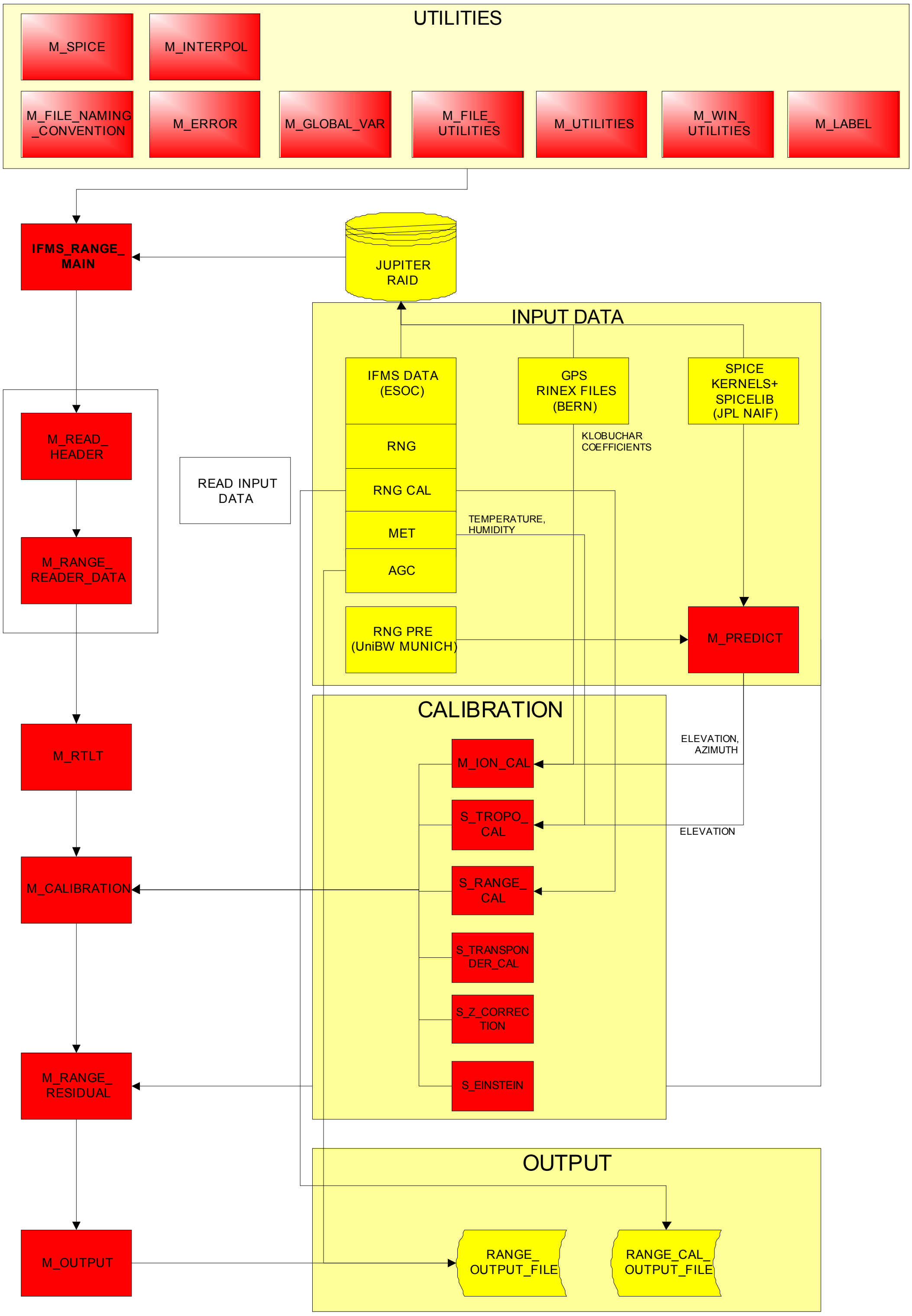
New Norcia

frequency band uplink	**Ground station geometric calibration**	
	S-band	**X-band**
S-band	59.47 nsec	59.77 nsec
X-band	59.58 nsec	59.87 nsec

2.3.1

2.3.2

2.4 FLOW DIAGRAM



3 SPECIFICATIONS OF MODULES

3.1 MODULE M_PREDICT

M_PREDICT accepts the SPICE Kernels for the MEX spacecraft and the NNO ground station. PREDICT estimates for the given time stamp TIME_RANGE the predicted range or OWLT and the ground station antenna elevation angles ELEVATION.

IFMS-SPEC-2210: M_PREDICT accepts input data from the SPICE kernels SPICE_MEX_S/C and SPICE_NNO_G/S.

IFMS-SPEC-2230: M_PREDICT accepts from Modules M_READ_INPUT_DATA the array TIME_RANGE, representing the observed range time stamps. M_PREDICT computes the estimated OWLT using SPICE.

IFMS-SPEC-2240: The result will be available as the array RANGE_PRE for modules M_RTLT, M_CALIBRATION and M_DOPPLER_OUTPUT.

IFMS-SPEC-2250: M_PREDICT computes the ground station elevation angles for each time stamp TIME_RANGE. The result will be available as ELEVATION in module M_CALIBRATION.

3.2 MODULE M_READ_INPUT_DATA

READ_INPUT_RANGE_DATA accepts IFMS level 1a range data at X-band or S-band (if available) from IFMS_RANGE.

All IFMS RANGE data files with equal reference time tags and increasing sequence number are stored in one data array. For these data files only one IFMS RANGE output file is being created with the time stamp of the data file with the lowest sequence number.

IFMS-SPEC-2310: READ_INPUT_RANGE_DATA accepts data from IFMS_RANGE.

IFMS-SPEC-2320: The file name format is defined in [1] section 5.2 and [2].

IFMS-SPEC-2330: The ranging file format is defined in [2].

IFMS-SPEC-2340: Module M_READ_INPUT_DATA extracts the parameter *actual_tone_indicator* from the IFMS_RANGE data header and makes it available for M_RTLT.

IFMS-SPRE-2350: Module M_READ_INPUT_DATA accepts only those data as valid input from IFMS_RANGE if *current_code >= 14* and *ambiguity = “TRUE”. Current_code* is made available for Module M_RTLT.

IFMS_SPEC_2360: Module M_READ_INPUT_DATA makes the time information as array TIME_RANGE available for the module M_PREDICT.

3.3 MODULE M_RTLT

Module M_RTLT computes the observed two-way round-trip light time from the actual measurement and the predicted range.

IFMS-SPEC-2410: Use the parameter *actual_tone_indicator* from the ranging file header (*actual_tone_indic*) and compute the actual tone frequency *tone_freq* from:

$$tone\_freq = acutual\_tone\_indic \cdot \frac{17.5 \cdot 10^{6}}{2^{32}} \quad Hz$$

IFMS-SPEC-2420: Compute the two-way light time ambiguity *amb* from

$$amb = \frac{2^{current\_code}}{tone\_freq} \quad \mathrm{sec}$$

Current_code is extracted from the IFMS_RANGE file and shall be greater equal 14.

IFMS-SPEC-2430: The two-way light time is the sum of the measured *delay* and *n* times the ambiguity. The value *n* needs to be determined from an estimate of the OWLT:

$$n = \mathrm{int}\left\{ \frac{\left[\tau_{predicted,one-way} - \frac{1}{2} delay \right]}{\frac{1}{2} amb} \right\}$$

n is an integer and $\tau_{predicted,one-way}$ is the predicted OWLT provided by Module M_PREDICT for the observed time stamp.

IFMS-SPEC-2440: Compute the RTLT from

$$\tau = n \cdot amb + delay$$

3.3.1

3.4 MODULE M_CALIBRATION

Module M_CALIBRATION uses the range calibration data obtained from the equipment propagation delay measurements before the tracking pass. The data are provided in IFMS_RANGE_CAL. An average calibration value and its r.m.s is computed. These calculated values together with the measured propagation delay are written into a RANG_CAL_OUTPUT outputfile with an appropriate PDS label. The format is specified in IFMS-SPEC-2730.

Further calibrations are the transponder delay time and the media propagation delay in the Earth troposphere and ionosphere.

IFMS-SPEC-2530: M_CALIBRATION accepts range calibration data from IFMS_RANGE_CAL.

IFMS-SPEC-2531: the file name format is defined in [1] in section 9.

IFMS-SPEC-2532: the file format of IFMS_RANGE_CAL is defined in [1] in section 9.

IFMS-SPEC-2540: range calibration

M_CALIBRATION computes the average equipment delay $<\tau_{cal}>$ and its standard deviation:

$$<\tau_{cal}> = \frac{1}{n}\sum_{i=1}^{n}\tau_{cal_i}$$

$$\sigma_{cal} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\tau_{cal_i} - <\tau_{cal}>\right)^2}$$

Only those data as valid input from IFMS_RANGE_CAL are accepted if *current_code >= 14* and *ambiguity = “TRUE”.*

IFMS-SPEC-2550: transponder delay

The transponder delay time $\tau_{transponder}$ is provided by the input table TRANSPONDER_CAL.

IFMS-SPEC-2555: Antenna Correction (Z-Correction)

The delay time τ_z caused by the G/S antenna geometry is provided by the input table by the input table GS_GEO_CAL

.

IFMS-SPEC-2560: Troposheric calibration

The path delay (unit is meter) of the dry and wet component of the Earth troposphere is (Hofmann-Wellenhoff et al., Global Positioning System, 4th Ed.):

$$\Delta_{dry}\left(E\right)=\frac{10^{-6}}{5}\frac{77.64\frac{p}{T}}{\sin\left(\sqrt{E^{2}+6.25}\right)}\left[40136+148.72\left(T-273.16\right)\right]$$

$$\Delta_{wet}\left(E\right)=\frac{10^{-6}}{5}\frac{-12.96T+3.718\cdot 10^{5}}{\sin\left(\sqrt{E^{2}+2.25}\right)}\frac{e}{T^{2}}11000$$

where p, T and e are the atmospheric pressure, Temperature and partial water vapour pressure, respectively, as observed at the ground station site.

These values are given in the IFMS_METEO file. The elevation angle E (unit in degrees) is provided by M_PREDICT.

The following transformations have to be applied:

	equation (20)	**IFMS_METEO**	**M_PREDICT**
pressure *p*	mbar	hPascal	-
Temperature *T*	Kelvin	°Celsius	-
water vapour partial pressure *e*	hPascal	-	-
humidity *h*	-	% humidity	-
elevation *E*	degrees	-	radian

The relation between the water vapour partial pressure and the humidity given in IFMS_METEO is:

$$e=6.108\cdot 10^{-2}\cdot humidity\left[\%\right]\cdot\exp\left\{\frac{17.393\left(T-272.15\right)}{T-33.95}\right\}$$

The total tropospheric calibration expressed as delay time in seconds is:

$$\tau_{tropo}=\frac{2}{c}\left\{\Delta_{dry}\left(E\right)+\Delta_{wet}\left(E\right)\right\}$$

where c is the speed of light with definition given in IFMS-DEF-1020. The factor 2 accounts for the two-way radio link.

IFMS-SPEC-2565: ionsopheric calibration
described in module M_IONO_CAL.

IFMS-SPEC-2566: relativistic group delay calibration
If no dual frequency measurements using the differential method are performed the ranging data must be corrected for the effects of the theory of General Relativity (GRT). **Figure 3.4-3.4.1** shows the geometric constellation relevant for our analysis.

Assuming a generalized Schwarzschild metric (where γ is the PPN parameter of General Relativity) the subroutine S_EINSTEIN calculates the additional two way delay $\tau_{einstein}$ caused by the gravity field of the sun by the following expression:

$$\tau_{einstein} = \frac{4GM}{c^3}\left[\frac{1+\gamma}{2}\ln\left(\frac{r_e + r_p + \rho}{r_e + r_p - \rho}\right)\right]$$

ρ, r_e and r_p are the coordinate distances between G/S and planet (satellite), the heliocentric distance of the G/S and the heliocentric distance of the planet (satellite), whereby γ is set to 1.0, because of the fact that $v_{s/c}$ is neglectible with rexpect to $c_{speed\ of\ light}$.

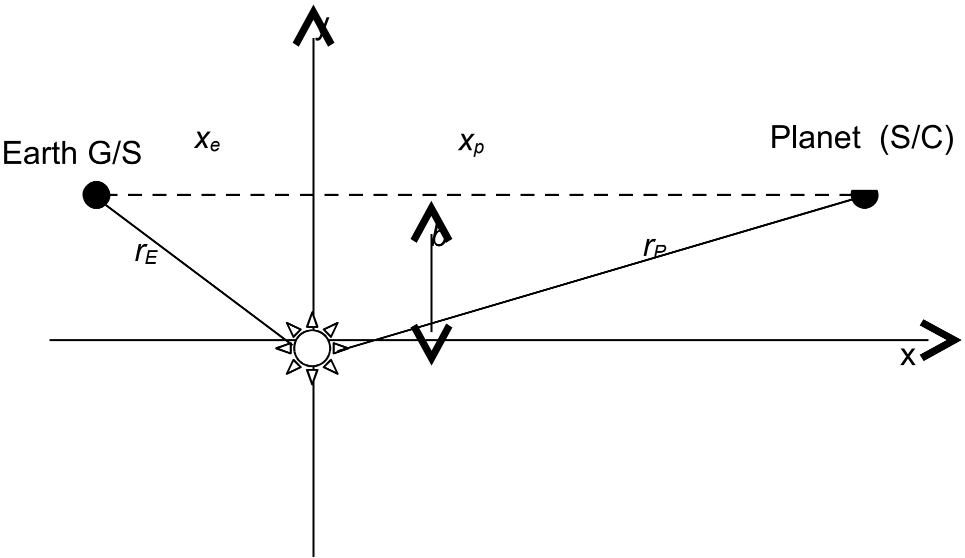


Figure 3.4-3.4.1:**Radar echo at planet P (S/C)**

IFMS-SPEC-2570: <u>total calibration</u>

The calibrated RTLT $\tau_{calibrated}$ is the observed RTLT τ derived in subroutine RTLT (IFMS-SPEC-2440) minus the average equipment delay $<\tau_{cal}>$ as derived in IFMS-SPEC-2540 minus the transponder delay $\tau_{transponder}$ as defined IFMS-SPEC-2550.

$$\tau_{calibrated} = \tau - <\tau_{cal}> - \tau_{transponder} - \tau_z - \tau_{iono}$$

3.5 MODULE M_IONO_CAL

Module M_IONO_CAL models the electron content of the Earth ionosphere at any local time and pointing direction of the ground station antenna and determines the path delay. This is done using the Klobuchar model introducing the Klobuchar coefficients from GPS measurements of the International GPS Service (IGS). The IGS is based on about 200 globally distributed permanent GPS tracking sites. The coefficients used by Module M_IONO_CAL come from one of the seven IGS Analysis Center: the Center for Orbit Determination in Europe (CODE) of the Astronomical Institute of the University of Berne (AIUB), Switzerland.
CODE generates Global ionosphere maps (GIM) on a daily basis using data from about 200 GPS/GLONASS sites of the IGS and other institutions. The vertical total electron content (VTEC) is modelled in a solar-geomagnetic reference frame using a spherical harmonics expansion up to degree and order 15. Piece-wise linear functions are used for representation in the time domain. The time spacing of their vertices is 2 hours, conforming with the epochs of the VTEC maps. Instrumental biases, so-called differential P1-P2 code biases (DCB), for all GPS satellites and ground stations are estimated as constant values for each day, simultaneously with the 13 times 256, or 3328 parameters used to represent the global VTEC distribution. The DCB datum is defined by a zero-mean condition imposed on the satellite bias estimates. P1-C1 bias corrections are taken into account if needed. To convert line-of-sight TEC into vertical TEC, a modified single-layer model mapping (MSLM) mapping function approximating the JPL extended slab model mapping function is adopted. The global coverage of the GPS tracking ground stations considered at CODE is shown figure 3.5.1 including abbreviations for station identification.

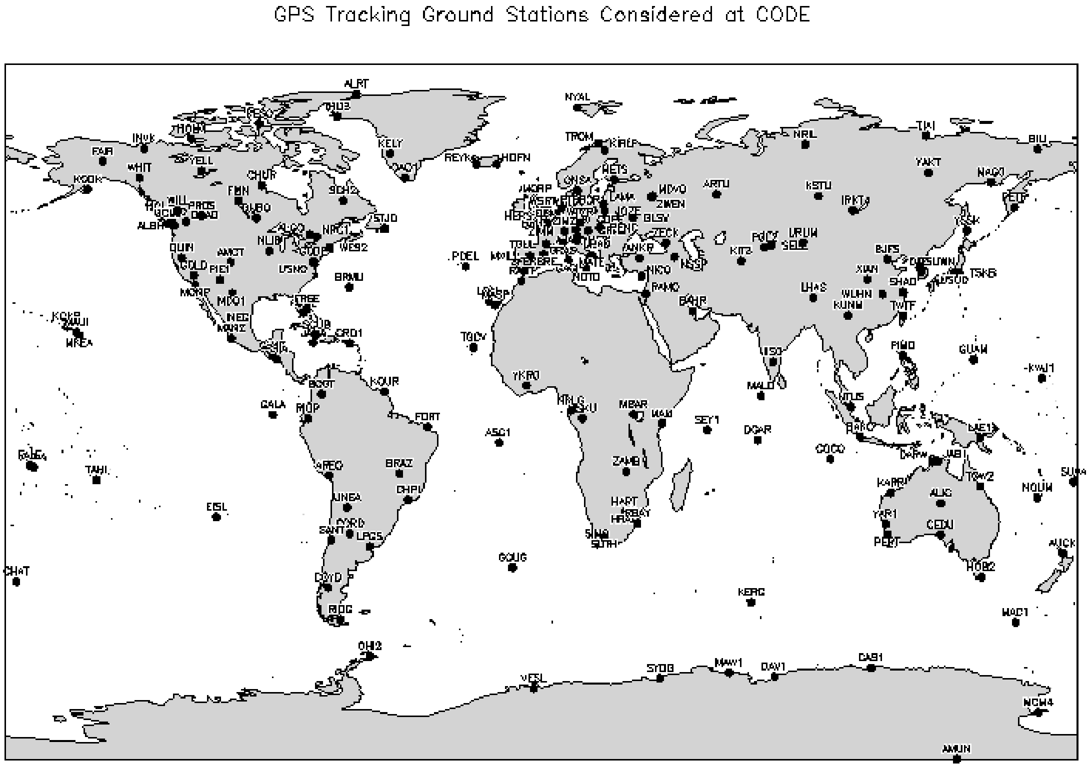


Figure 3.5-3.5.1:**GPS Tracking Ground Stations**

CODE computes Klobuchar-style ionospheric coefficients (alphas and betas) best fitting the IONosphere map EXchange data (IONEX) on a regular basis. The description how the Klobuchar coefficients are computed and on which ionopsheric model they are based on can be found in ANNEX B.

The data files containing the Klobuchar coefficients are named CGIMddd0.yyN, where ddd and yy substitute doy and 2-digit year. Those coefficients derived from a final IONEX product are stored under ftp://ftp.unibe.ch/aiub/CODE/ in yyyy-specific subdirectories as of 1995. For the few days where the final product is not yet available, rapid as well as predicted coefficients serving real-time applications may be found generally at ftp://ftp.unibe.ch/aiub/CODE/. CGIM2410.04N_R contains the latest set of rapid coefficients; CGIM2420.04N_P and CGIM2430.04N_P2 contain the current 1-day and 2-day predicted coefficients, respectively.

Unlike the original Klobuchar ionosphere model which is based on a total of 370 possible sets of base coefficients and which is therefore of discrete nature, the model derived by CODE is not subject to a similar restriction. All the night-time TEC level of this type of ionosphere model is hard-wired to 5 nanoseconds of ionospheric delay on the first GPS frequency (corresponding to approximately 9 TECU). Because the Klobuchar-style TEC parameterization may be unpleasant at the polar caps and especially at the poles, CODE displays a corresponding warning in the RINEX navigation data files in case the TEC above a latitude of 75 degrees reaches day-time level. The format of RINEX data files is described in ANNEX C.

The module is currently only valid for the NNO ground station.

IFMS-SPEC-2610: Module M_IONO_CAL accepts the actual needed Klobuchar coefficients (described above) from input file ION_COEFF. The input file can be downloaded from

ftp.unibe.ch/aiub/CODE/

M_IONO_CAL needs several input parameters, which are listed in the table below.

Parameter	Description	Unit
Phi	Geodetic latitude of receiver	Degree
Lambda	Geodetic longitude of receiver	Degree
TOW	Time of Week	Degree

Beta	The coefficients of a cubic equation representing the amplitude of the vertical delay	
Alpha	The coefficients of a cubic equation representing the period of the model	

IFMS-SPEC-2615: The output of Module M_IONO_CAL is the ionospheric slant range correction **d_tau_iono**. The unit of **d_tau_iono** is seconds. The calculation of **d_tau_iono** is described in **IFMS-SPEC-2620.**

IFMS-SPEC-2620: The computation of the ionospheric slant range correction **d_tau_iono** depends on the local time at the ground station side. For the calculation of **d_tau_iono** the following parameters are used:

1. **Local Time t:**

   t = 4.32·long_i + TOW

2. **Azimuth a (in radian):**

   a = azimuth·pi /180
   !

3. **Elevation angle e (in semicircles):**

   e = elev·1./180
   !

4. **Earth Centered angle psi:**

   psi = 0.0137/ (e+0.11) - 0.022

5. **Subionospheric longitude long_i :**

   long_i = lambda·1./180.+ (psi·DSIN(a)/DCOS(lat_i·pi))

6. **Subionospheric latitude lat_i :**

   lat_i = phi·1./180+ psi·DCOS(a)

7. **Time of the Week TOW (output of the subroutine S_GPSTIME)**

   t = DMOD(t,86400.) !

8. **Slant factor sf:**

$sf = 1. + 16. \cdot (0.53-e)^3$!

9. **Period of model PER:**

If PER less than 72000.D0

PER = 72000.

Else

$PER = beta(1) + beta(2) \cdot lat\_m + beta(3) \cdot lat\_m^2 + beta(4) \cdot lat\_m^3$

10. **Phase of the model x (Maximum at 14.00 =! 50400 sec local time):**

$x = 2. \cdot pi \cdot (t-50400.) / PER$!

11. **Amplitude of the model AMP:**

$AMP = alpha (1) + alpha (2) \cdot lat\_m + alpha (3) \cdot lat\_m^2 + alpha(4) \cdot lat\_m^3$

12. **Ionospheric slant correction d_tau_iono:**

Night (DABS(x) greater Than 1.57):

d_tau_iono = sf · (5.D-9)

Day:

$d\_tau\_iono\ 1 = sf \cdot (5.D-9 + AMP*(1.D0 - x^2/2. + x^4/24.))$

3.6 MODULE M_OUTPUT

Module M_OUTPUT generates the IFMS Range Outputfiles. Within the M_OUTPUT the subroutine S_RNG_OUTPUT computes for each frequency band the ranging residuals, expressed as propagation time, between the observed TWLT and the predicted TWLT. This predicted TWLT includes the troposheric correction **(IFMS-SPEC-2560)** and the relativistic correction **(IFMS-SPEC-2566:**).

$$\tau_{predicted} = \tau_{TWLT,UBW} + \tau_{tropo} + \tau_{enstein}$$

IFMS-SPEC-2640: M_OUTPUT accepts predicted RTLT as interpolated from PREDICT_FILE in M_MODULE PREDICT from the given array TIME_RANGE.

IFMS-SPEC-2645: S_RNG_OUTPUT computes the range residuals (range delay) at S-band or X-band expressed as residual in the round-trip-light time τ

$$\Delta\tau = \tau_{calibrated} - \tau_{predicted}$$

3.7

IFMS-SPEC-2710: The RANGE_OUTPUT file name is defined as

rggIFMSL02_sss_yydddhhmm_qq.TAB

The definitions are given in Table 3-3.1.

placeholder	description	example
r	spacecraft name M = MEX R = Rosetta V = VEX	M
gg	ground station xx = ESA Cerbreros 32 = ESA New Norcia (tbc)	32
IFMS	Data source IFMS = IFMS file	IFMS
L02	Data level L02	L02
sss	File type RGS = calibrated S-band ranging RGX = calibrated X-band ranging	RGX
yy	year	03
ddd	day of year	180
hhmm	start time of first data file in hour, minute	2345
qq	not used	00
TAB	Extension .TAB data file	TAB

Table 3-3.1: RANGE_OUTPUT file name Definition

SCA-SPEC-2720: The format of the X-band RANGE_OUTPUT file is defined in Table 3-3.2.
All quantities not available for the appropriate output file are set to the INVALID CONSTANT=-999999.999999999.

column	description	unit	resolution
1	Sample number		
2	time in ISO format		
3	fractions of day of year	days	10^{-7} days
4	MJD since 01.01.2000	MJD	
5	Geometrical Impact Parameter (Distance of the s/c from the center of mass of the appropriate target)	Kilometer	10^{-7} meters
6	Observed TWLT X-band	Seconds	nsec
7	calibrated TWLT X-band	Seconds	nsec
8	TWLT delay X-band	Seconds	nsec
9	Differential TWLT	Seconds	nsec
10	Range calibration G/S equipment	seconds	nsec
11	Range Predict	Seconds	nsec
12	Range Residuum (Column 7 minus column 11	Seconds	nsec
13	AGC X-band	dBm	0.1 dBm

Table 3-3.2: Definition of X-band RANGE_OUTPUT file format

SCA-SPEC-2721: The format of the S-band RANGE_OUTPUT file is defined in Table 3-3.3.
All quantities not available for the appropriate output file are set to the INVALID CONSTANT=-999999.999999999.

column	description	unit	resolution
1	Sample number		
2	time in ISO format		
3	fractions of day of year	days	10^{-7} days
4	MJD since 01.01.2000	MJD	
5	Geometrical Impact Parameter (Distance of the s/c from the center of mass of the appropriate target)	Kilometer	10^{-7} meters
6	Observed TWLT S-band	Seconds	nsec
7	calibrated TWLT S-band	Seconds	nsec
8	TWLT delay S-band	Seconds	nsec
9	Differential TWLT	Seconds	nsec
10	Range calibration G/S equipment	seconds	nsec
11	Range Predict	Seconds	nsec
12	Range Residuum (Column 7 minus column 11)	Seconds	nsec
13	AGC S-band	dBm	0.1 dBm

Table 3-3.3: Definition of S-band RANGE_OUTPUT file format

3.8 RANGE CALIBRATION OUTPUT

IFMS-SPEC-2730: The RANGE_CAL_OUTPUT file name is defined as

rggIFMSL02_sss_yydddhhmm_qq.TAB

The definitions are given in Table 3-3.4.

placeholder	description	example
r	spacecraft name M = MEX R = Rosetta V = VEX	M
gg	ground station xx = ESA Cerbreros 32 = ESA New Norcia (tbc)	32
IFMS	Data source IFMS = IFMS file	IFMS
L02	Data level L02	L02
sss	File type RCS = S-band ranging calibration RCX = band ranging calibration	RCX
yy	year	03
ddd	day of year	180
hhmm	start time of data in hour, minute	2345
qq	not used	00
TAB	Extension .TAB data file	TAB

Table 3-3.4: RANGE_CAL_OUTPUT file name Definition

3.9 RANGE LOGFILE OUTPUT

IFMS-SPEC-2735: The RANGE_LOG_OUTPUT file name is defined as

rggIFMSL02_sss_yydddhhmm_qq.LOG

The definitions are given in Table 3-3.45.

placeholder	description	example
r	spacecraft name M = MEX R = Rosetta V = VEX	M
gg	ground station xx = ESA Cerbreros 32 = ESA New Norcia (tbc)	32
IFMS	Data source IFMS = IFMS file	IFMS
L02	Data level L02	L02
sss	File type RCS = S-band ranging calibration RCX = band ranging calibration	RCX
yy	year	03
ddd	day of year	180
hhmm	start time of first data file in hour, minute	2345
qq	not used	00
TAB	Extension .TAB data file	TAB

Table 3-5: RANGE_LOG_OUTPUT file name Definition

SCA-SPEC-2740: The format of the X-band RANGE_CAL_OUTPUT file is defined in Table 3-3.5.

column	description	unit	resolution
1	Sample number		
2	time in ISO format		
3	fractions of day of year	days	10^{-7} days
4	MJD since 01.01.2000	MJD	
5	Mean average value of X-band equipment propagation delay	Seconds	nsec
6	X-band equipment propagation delay	Seconds	nsec
7	Root Mean Square of X-band equipment propagation delay	Seconds	nsec

Table 3-3.5: Definition of X-band RANGE_CAL_OUTPUT file format

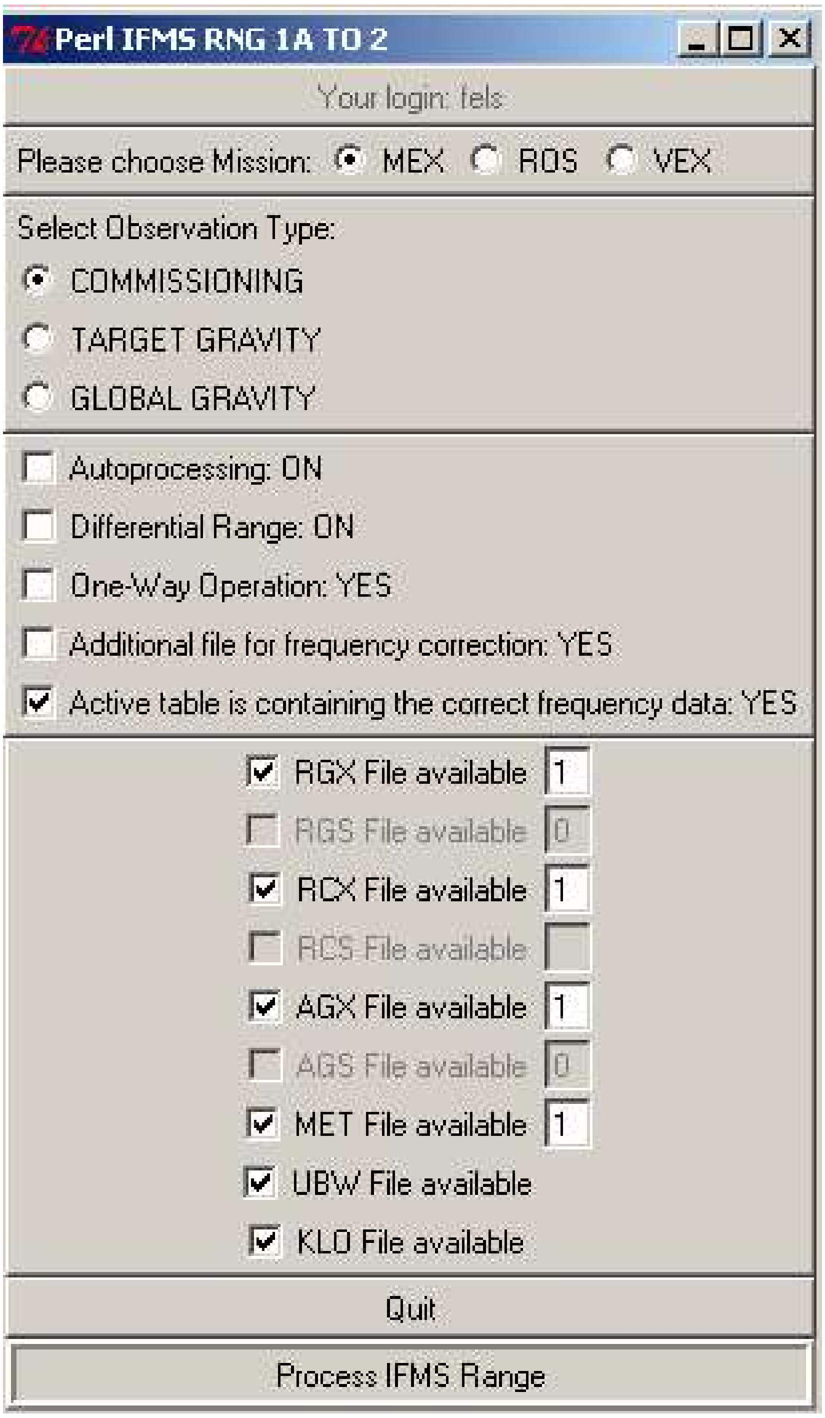
SCA-SPEC-2741: The format of the S-band RANGE_CAL_OUTPUT file is defined in Table 3-3.6

column	description	unit	resolution
1	Sample number		
2	time in ISO format		
3	fractions of day of year	days	10^{-7} days
4	MJD since 01.01.2000	MJD	
5	Mean average value of S-band equipment propagation delay	Seconds	nsec
6	X-band equipment propagation delay	Seconds	nsec
7	Root Mean Square of S-band equipment propagation delay	Seconds	nsec

Table 3-3.6: Definition of S-band RANGE_CAL_OUTPUT file format

4 PERL GRAPHICAL USER INTERFACE PERL_FIMS.PL

This section describes the structure and the usage of a PERL TK Graphical User Interface (GUI), named **perl_ifms.pl**, with which the IFMS RANGE Software can be easily configured and executed. The GUI is shown in the figure below:



Your login: fels

Please choose Mission: ● MEX ○ ROS ○ VEX

Select Observation Type:
● COMMISSIONING
○ TARGET GRAVITY
○ GLOBAL GRAVITY

☐ Autoprocessing: ON
☐ Differential Range: ON
☐ One-Way Operation: YES
☐ Additional file for frequency correction: YES
☑ Active table is containing the correct frequency data: YES

☑ RGX File available 1
☐ RGS File available 0
☑ RCX File available 1
☐ RCS File available
☑ AGX File available 1
☐ AGS File available 0
☑ MET File available 1
☑ UBW File available
☑ KLO File available

The main function of this GUI is creating a so called **process_option.txt** file, which incudes all information needed for processing IFMS Range data. In case of autoprocessing a list of existing logfiles is opened and used as input parameters. After starting the Perl script the user have to enter his LOGIN. This LOGIN can be seen in the top widget of the GUI and it is stored as additional information in a logfile, which is being created during processing. This logfile mainly includes informations of the input and output data and the IFMS Range configuration. Together with this information the errors are listed, which occurred during the IFMS Range processing. An example logfile is shown below:

```
MEX

GLOBAL GRAVITY

FLAGS FROM PROCESS_OPTIONS FILE:
-------------------------------
F    Differential Range ON
T    Processing with UniBW Predict
F    Processing with AGC
T    Processing with CGIM
T    Processing with RCL
F    Processing with MET
F    Additional file for frequency correction
F    One-Way Mode
F    Active table is containing the correct frequency data

NUMBER OF INPUT FILES:
---------------------
01    Number of RGX files
00    Number of RGS files
00    Number of AGX files
00    Number of AGS files
00    Number of MET files

FILES USED FOR PROCESSING:
-------------------------
D:\data\mars_express\300\NN11_MEX1_2004_300_OP_RG_235105_0000.raw
D:\data\mars_express\300\NN11_MEX1_2004_300_CL_RG_202229_0000.raw
D:\data\mars_express\300\predict_300.txt
D:\data\mars_express\300\CGIM3000.04N\CGIM3000.04N

FILES CREATED DURING PROCESSING:
-------------------------------
D:\data\mars_express\300\M32ICL1L02_RGX_043002351_00.TAB
D:\data\mars_express\300\M32ICL1L02_RGX_043002351_00.LBL
D:\data\mars_express\300\M32ICL1L02_RCX_043002022_00.TAB
D:\data\mars_express\300\M32ICL1L02_RCX_043002022_00.LBL
```

```
CONFIGURATION INFO:
--------------------
UPLINK-FREQUENCY X-BAND:     7166758739.9976720809936523
DOWNLINK-FREQUENCY X-BAND:   8420223886.7796421051025391
SAMPLE-INTERVAL X-BAND:      1.000
TRANSPONDER-RATIO X-BAND:    880/749

PROCESSING INFO:
----------------
PRODUCER ID:       fels
NO DIFFERENTIAL RANGE
PLASMA-CORRECTION DONE WITH KLOBUCHAR-MODEL

ERRORS:
-------
No Errors during processing
```

5 ANNEX A

5.1 MEX TRANSPONDER GROUP DELAY VALUES

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6 ANNEX B

6.1 EARTH KLOBUCHAR IONOSPHERE MODEL

MAPPING AND PREDICTING THE IONOSPHERE

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ABSTRACT

The Center for Orbit Determination in Europe (CODE) produces daily maps of the Earth's ionosphere on a regular basis since January 1, 1996. These global ionosphere maps (GIMs) are derived from exactly the same GPS tracking data — doubly differenced carrier phase measurements — as those used for the determination of CODE core products delivered to the IGS like precise GPS orbits, earth orientation parameters (EOPs), station coordinates and velocities. For the ionospheric product we have to analyze the so-called *geometry*-free linear combination (LC), which primarily contains ionospheric information, as opposed to the *ionosphere*-free LC, which contains the "geometrical" information and completely eliminates the influence of the ionospheric refraction (ignoring higher-order terms). At present (March 1998), the GPS tracking network processed at CODE consists of more than 110 globally distributed stations of the International GPS Service for Geodynamics (IGS).

After reprocessing all 1995 IGS data using the "Bernese Processing Engine" [Rothacher et al., 1996a], a long-time series of daily GIM parameters covering a time span of about 3.2 years is at our disposal. On the one hand this ionosphere time series reveals the evolution of the total electron content (TEC) on a global scale, on the other hand it indicates that *short*-term as well as *long*-term predictions for CODE GIM parameters are possible. We discuss the time series for a few selected TEC parameters and develop a method to predict the TEC parameters. Futhermore, we describe how the temporal resolution can be increased when using spherical harmonic (SH) expansions to model the global TEC. First attempts estimating 2-hour maps are encouraging.

CODE'S IONOSPHERE PRODUCTS — AN OVERVIEW

The principles of the TEC mapping technique used at CODE were described in [Schaer et at., 1995] and [Schaer et al., 1996a].

At present the following ionosphere products are generated on a routine basis:

- 24-hour global ionosphere maps (GIMs) are produced using double-difference phase *or* phase-smoothed code observations. The *phase*-derived TEC maps proved their usefulness for ambiguity resolution (AR) on long baselines [Rothacher et al., 1996b].
- *Rapid* global maps are available with a delay of about 12 hours, the *final* ones after 3 days (in the IONEX format [Schaer et al., 1998]).
- Regional (European) maps are produced as well and are also used to support AR. On the average 90% of the initial carrier phase ambiguities can be resolved reliably — without making use of code measurements. Daily IONEX files containing hourly snapshots of the ionosphere are made available via anonymous ftp.
- Daily sets of differential code biases (DCBs) for all GPS satellites (and the contributing receivers) are estimated at CODE since October 1997.

Figure 1 shows the daily DCB estimates (dots) for 27 GPS satellites from day 022, 1998, to day 071, 1998, and the combined DCBs (circles) aligning all satellite-specific DCBs in the sense that the overall mean becomes *zero* (to obtain a virtual, but very stable reference). However, there are a couple of PRNs with *drifting* DCBs with respect to the remaining PRNs. PRN 08, which was launched few months ago, shows a significant drift of almost -0.5 ns over 50 days. We observe an increased root-mean-square error (RMS) for this satellite when assuming and modeling the DCBs as constant quantities (see Figure 1 and Table 1).

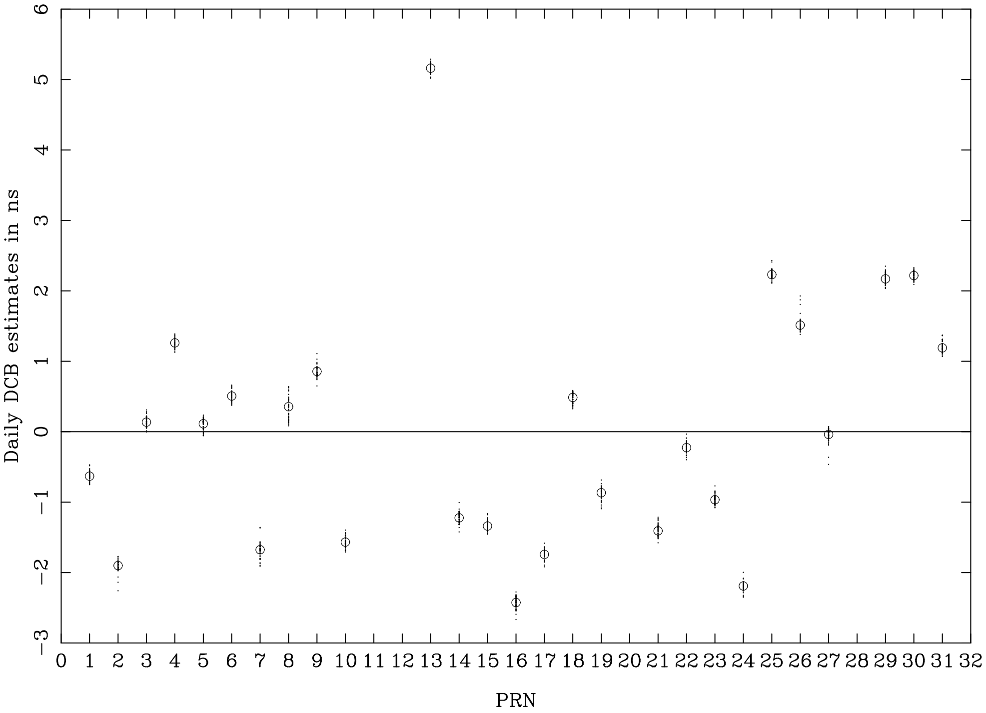


Figure 1. Daily PRN-specific DCB estimates (dots) for 27 GPS satellites from day 022, 1998, to day 071, 1998, and combined DCBs (circles)

The *combined* values of the satellite-specific DCBs taking into account the variance information of the individual solutions are listed in Table 1. In addition, the weighted RMS (WRMS) of the daily estimation is given for each PRN. The total WRMS of the 50-day DCB combination amounts to 0.08 ns. Let us mention that the estimated *receiver-specific* DCBs are of the order of ±15 ns and show a day-to-day scattering highly depending on the station considered. Note that the DCB results presented here originate from a special solution where we simultaneously estimate n station-specific TEC models leading to $16\,n$ TEC plus $n+27$ DCB parameters per day in total, where n is the number of stations processed.

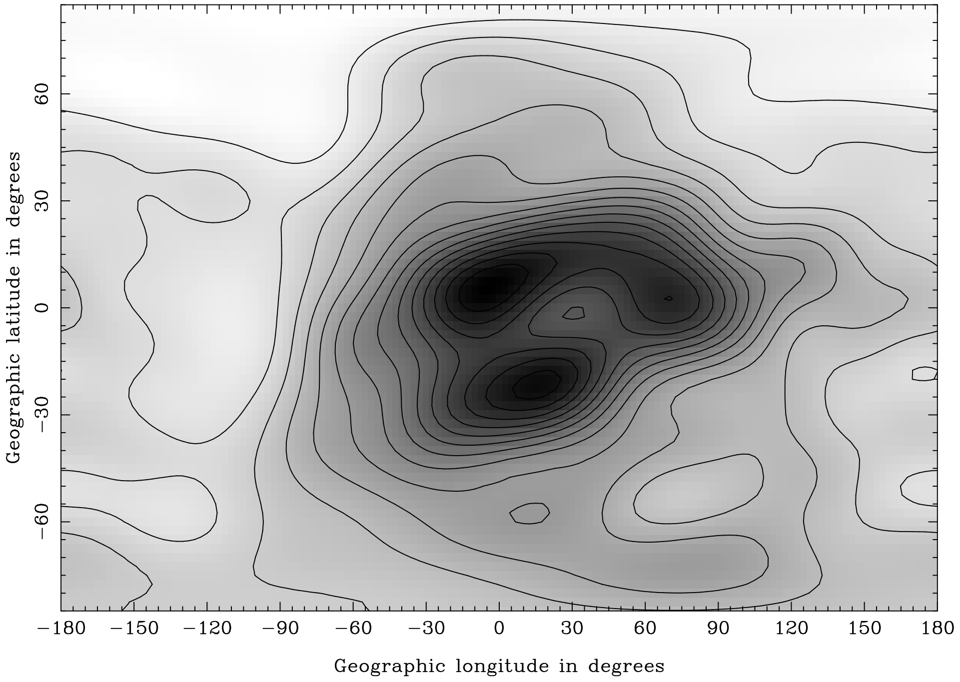
Table 1. Combined DCBs and weighted RMS errors of daily estimation

PRN	DCB (ns)	WRMS (ns)	PRN	DCB (ns)	WRMS (ns)
01	−0.63	0.06	17	−1.74	0.06
02	−1.90	0.07	18	+0.49	0.07
03	+0.14	0.06	19	−0.87	0.08
04	+1.26	0.06	21	−1.41	0.08
05	+0.11	0.07	22	−0.23	0.06
06	+0.51	0.07	23	−0.97	0.06
07	−1.68	0.11	24	−2.19	0.06
08	+0.35	0.16	25	+2.23	0.05
09	+0.86	0.07	26	+1.51	0.09
10	−1.57	0.07	27	−0.04	0.08
13	+5.16	0.06	29	+2.17	0.07
14	−1.22	0.07	30	+2.22	0.06
15	−1.34	0.07	31	+1.19	0.07
16	−2.43	0.08			

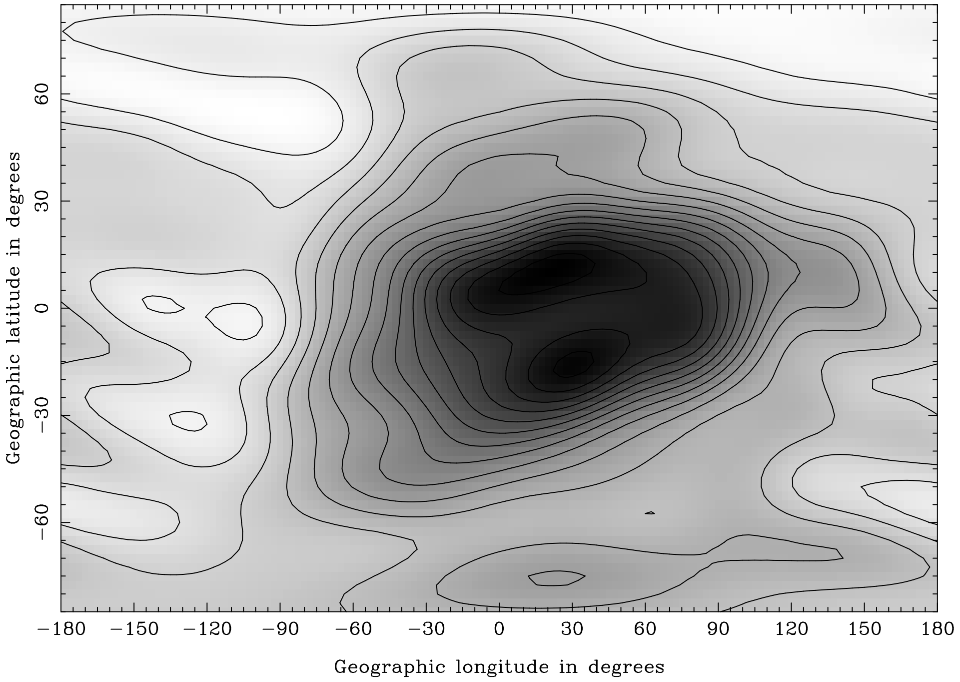
Figure 2 shows snapshots of (a) a *phase*-derived and (b) a *code*-derived 24-hour TEC map for day 017, 1998 (taken at 12:00 UT). The number of contributing stations was 79 on that particular day. Light fields indicate small TEC, dark ones large TEC (up to 37.6 and 39.0 TECU here). The level lines are drawn at intervals of 2.5 TECU. There is no significant difference between the two maps.

LONG-TIME SERIES OF GLOBAL TEC PARAMETERS

The long-time series of global TEC parameters available at CODE covers over 1168 days and includes $(8+1)^2 = 81$ SH coefficients (the SH expansion was truncated at degree and order 8). The zero-degree SH coefficient representing the mean TEC on a global scale characterizes the ionospheric activity pretty well. The evolution of this particular TEC parameter during a period of low solar activity is shown in Figure 3. The daily estimates (dots) and a smoothed curve to better visualize the behavior are given. One recognizes a long-term trend caused by the 11-year solar cycle, annual and semi-annual variations, and relatively strong short-term fluctuations with periods of the order of 27 days due to the Sun's rotation. We clearly see maxima at equinox and minima at solstice, however, the minima in summer are more pronounced than those in winter. The recent ionospheric minimum was observed in summer 1996.



(a) *Phase*-derived TEC map



(b) *Code*-derived TEC map

Figure 2. 24-hour TEC maps for day 017, 1998

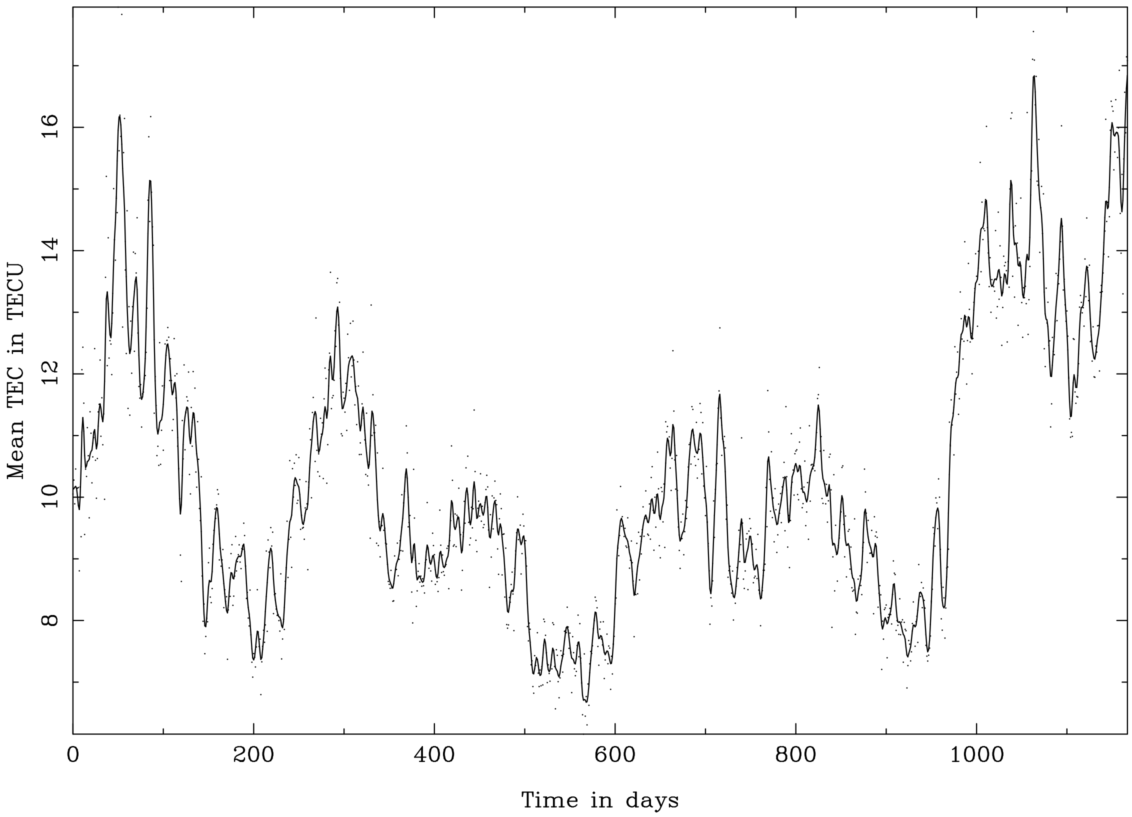
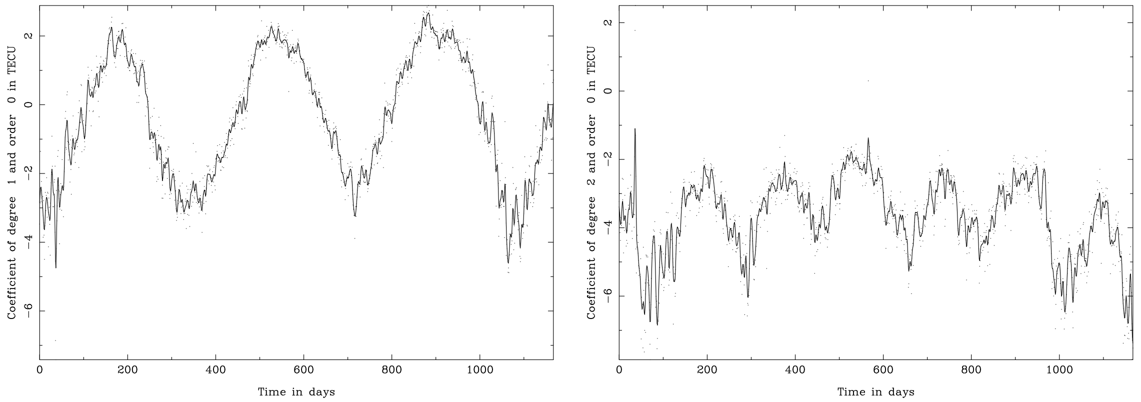


Figure 3. Zero-degree coefficient (mean TEC) from day 001, 1995 to day 072, 1998

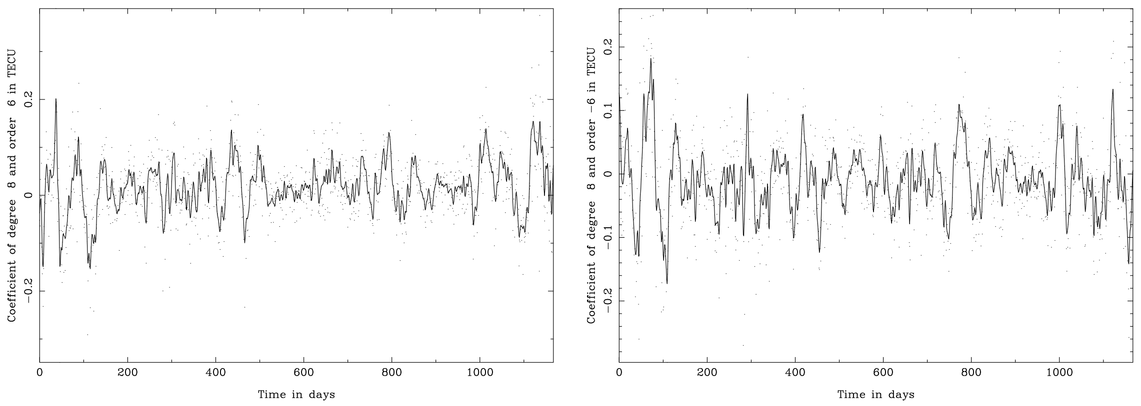
Figures 4 and 5 illustrate a few other SH coefficients showing similar periodicities and features as mentioned above.



(a) Term of degree 1 (and order 0)

(b) Term of degree 2 (and order 0)

Figure 4. Zonal SH terms



(a) Cosine term of degree 8 and order 6

(b) Sine term of degree 8 and order 6

Figure 5. Tesseral SH terms

When correlating the mean TEC values and the 10.7-cm solar flux, the correlation factor is almost 0.8, reaching its maximum at a lag of 1 day.

PREDICTING THE IONOSPHERE

Let us split up the "ionospheric signal" $\boldsymbol{l}$ — a time series of SH TEC parameters $e_{ij}(t_k)$ — into a *deterministic* component $\boldsymbol{d}$, which can be represented by a so-called trend function $\Phi(t)$, a *stochastic* component $\boldsymbol{s}$, and a noise component $\boldsymbol{n}$:

$$\boldsymbol{l} = \boldsymbol{d} + \boldsymbol{s} + \boldsymbol{n} \quad \text{or} \quad \boldsymbol{l} - \boldsymbol{\Phi}(\boldsymbol{x}_0) = \boldsymbol{A}\,\boldsymbol{x} + \boldsymbol{s} + \boldsymbol{n}. \tag{1}$$

As our trend function we use a harmonic expansion with a few prominent periods (11, 1, and 1/2 years)

$$\Phi(t) = a_0 + \sum_{i=1}^{m} \left(a_i\,\cos(\omega_i\,t) + b_i\,\sin(\omega_i\,t)\right) \quad \text{with} \quad \omega_i = \frac{2\,\pi}{\tau_i}. \tag{2}$$

The unknown parameters $\boldsymbol{x}$ of the trend function are estimated in a least-squares adjustment

$$\boldsymbol{x} = \left(\boldsymbol{A}^T\,\boldsymbol{C}_{zz}^{-1}\,\boldsymbol{A}\right)^{-1}\,\boldsymbol{A}^T\,\boldsymbol{C}_{zz}^{-1}\,\left(\boldsymbol{l} - \boldsymbol{\Phi}(\boldsymbol{x}_0)\right), \tag{3}$$

where

$$\boldsymbol{x}^T = [a_0, a_1, b_1, \ldots, a_n, b_n] \quad \text{and} \quad \boldsymbol{C}_{zz} = \boldsymbol{C}_{ss} + \boldsymbol{C}_{nn}. \tag{4}$$

$\boldsymbol{C}_{ss}$ and $\boldsymbol{C}_{nn}$ are the covariance matrices for the actual "signal" and the pure "noise", respectively. Finally, if we perform short-term predictions (or interpolations), the *stochastic* component $\boldsymbol{s}$ is of interest, too:

$$\begin{bmatrix} \boldsymbol{s} \\ \boldsymbol{n} \end{bmatrix} = \begin{bmatrix} \boldsymbol{C}_{ss} \\ \boldsymbol{C}_{nn} \end{bmatrix} \boldsymbol{C}_{zz}^{-1} \, (\boldsymbol{l} - \boldsymbol{\Phi}(\boldsymbol{x})) \, . \tag{5}$$

The autocovariance function γ, which is used to set up the covariance matrices $\boldsymbol{C}_{ss}$ and $\boldsymbol{C}_{zz}$, may be evaluated as

$$\gamma(h\,\Delta t) = \frac{1}{n} \sum_{k=1}^{n-|h|} (e_{ij}(t_k) - \Phi(t_k)) \, (e_{ij}(t_{k+|h|}) - \Phi(t_{k+|h|})). \tag{6}$$

$h\,\Delta t$ denotes the lag; $\gamma(0)$ is the variance of the stochastic component.

The autocovariance function (ACF) of the mean TEC, i. e., the SH coefficient e_{00}, is given in Figure 6. We notice that the ACF mainly reflects the Sun's rotation period of approximately 27 days.

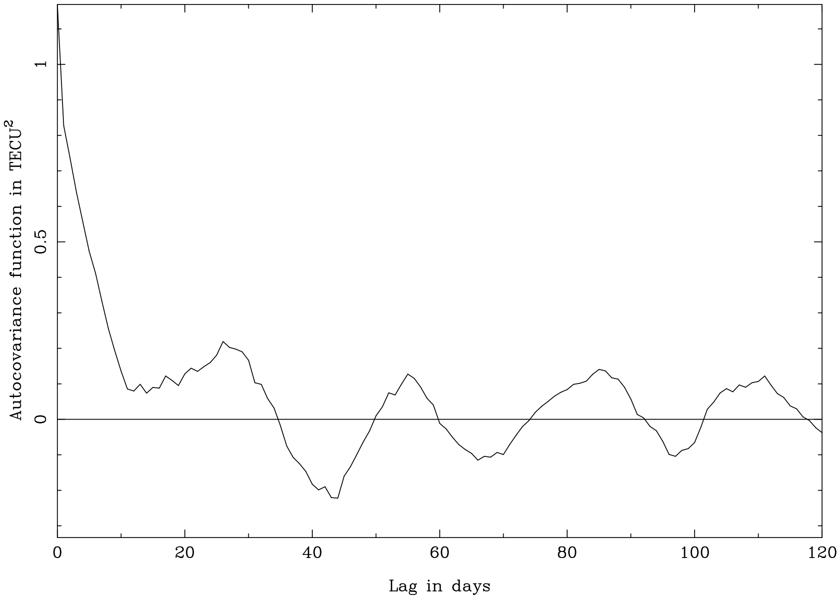
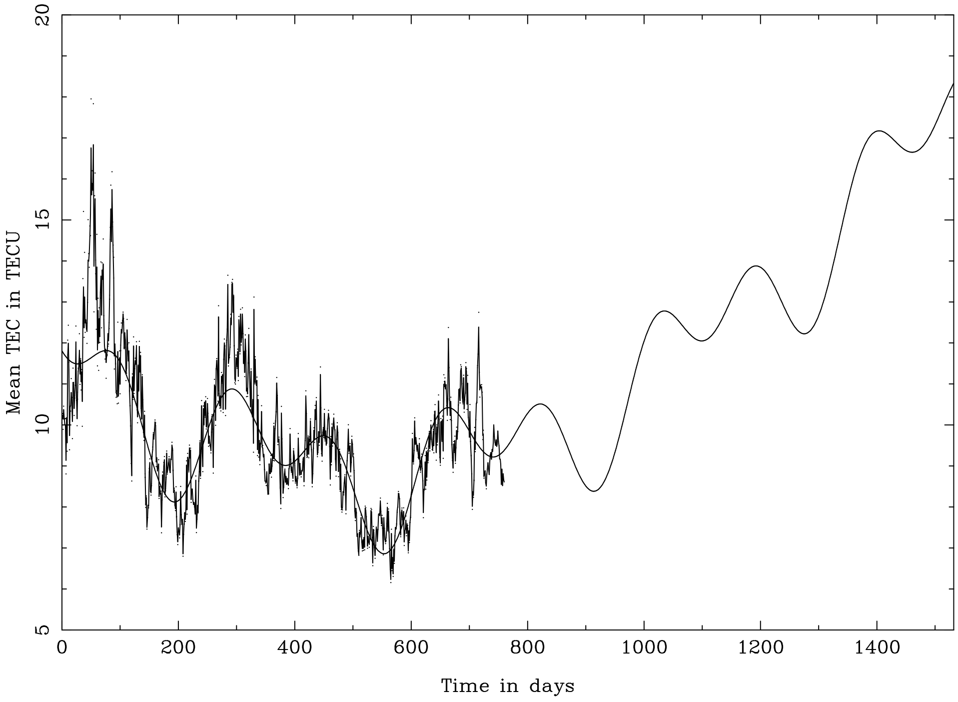
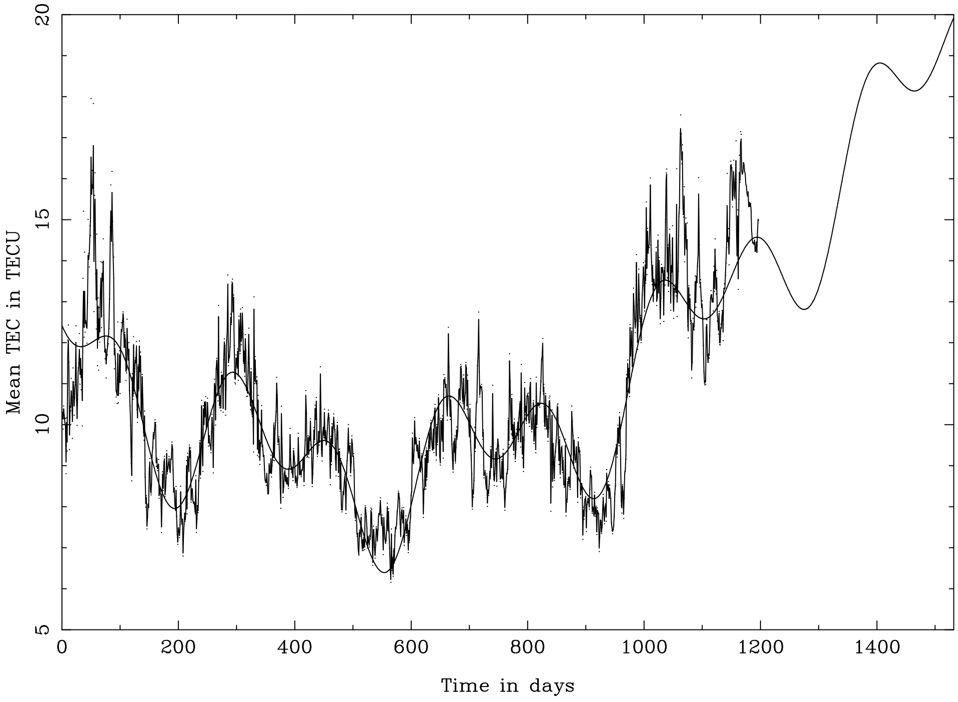


Figure 6. Autocovariance function of zero-degree coefficient for lags up to 120 days

Figure 7 shows the results when predicting (and interpolating) the mean TEC based on (a) a two-year time series *only* and (b) the complete time series. The daily GIM estimates are represented by dots. The trend function $\Phi(t)$ is given by the solid, smooths line and follows the general signal pretty well. It is amazing, considering that the time span of two years is quite short compared to a solar cycle, how well the extrapolated trend function shown in Figure 7a matches the real TEC observations shown in Figure 7b. The rapidly varying line also includes the *stochastic* component covering a prediction length of 30 days.



(a) 1995–1996 GIM data



(b) All GIM data

Figure 7. Prediction of mean TEC based on (a) a two-year time series and (b) the complete time series

When inspecting Figure 7 we see that the prediction consisting of $\boldsymbol{d}+\boldsymbol{s}$ does not exactly match the daily estimates because the matrix $\boldsymbol{C}_{nn}$ is not a zero matrix but contains the variances provided by the primary ionosphere parameter estimation.

By performing the least-squares collocation step for each SH coefficient using the same prediction length, merging the predicted TEC coefficients to a full set of SH parameters, and writing a corresponding GIM file, we get a procedure that allows us to predict entire CODE GIMs! A software tool solving that task has been developed.

HIGH TEMPORAL RESOLUTION TEC USING SPHERICAL HARMONIC EXPANSIONS

In this section we discuss a method on how to increase the temporal resolution of the TEC representation when using spherical harmonic (SH) expansion.

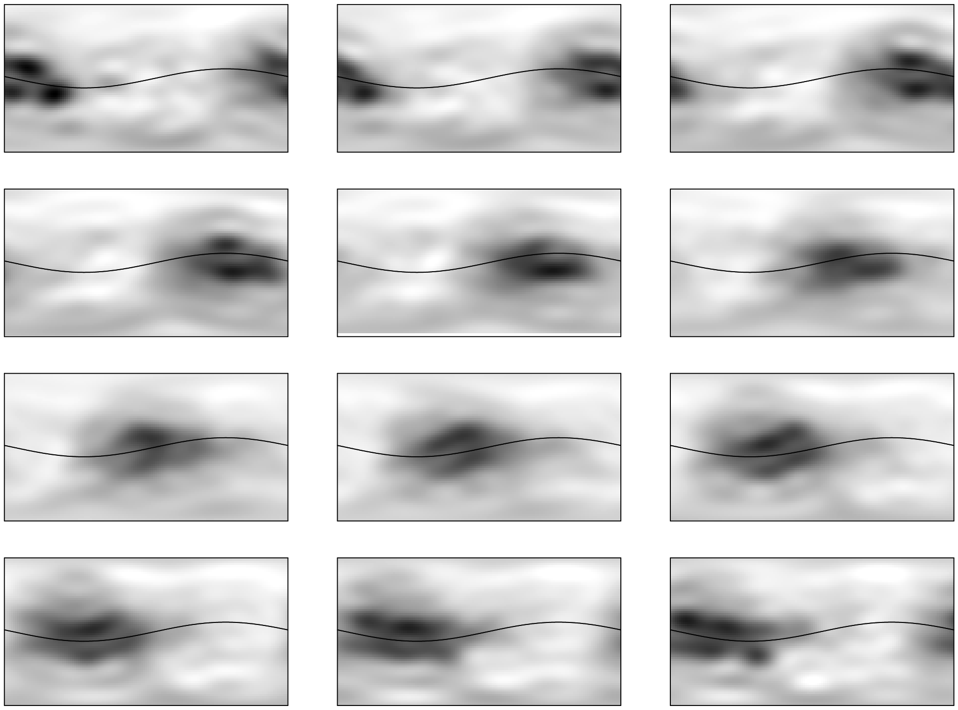
SH expansions are well suited to model time-independent quantities given on a spherical surface. When dealing with the ionosphere, the entire sphere is probed by GPS stations when deriving one-day TEC maps. The disadvantage is a poor temporal resolution because of the assumption of a “frozen” ionosphere co-rotating with the Sun. However, the general ionospheric behavior may well be described with daily TEC maps. When generating several TEC maps per day, one has to expect at times unreasonable — very high or negative — TEC estimates in regions where no stations are located. One may avoid such problems by limiting the variations between consecutive TEC maps with “relative” a priori constraints between consecutive maps by adding “relative” pseudo-observations of the type

$$\Delta e_{ij} = e_{ij}(t_k) - e_{ij}(t_{k-1}) = 0 \quad \text{for} \quad k = 2, \ldots, n \tag{7}$$

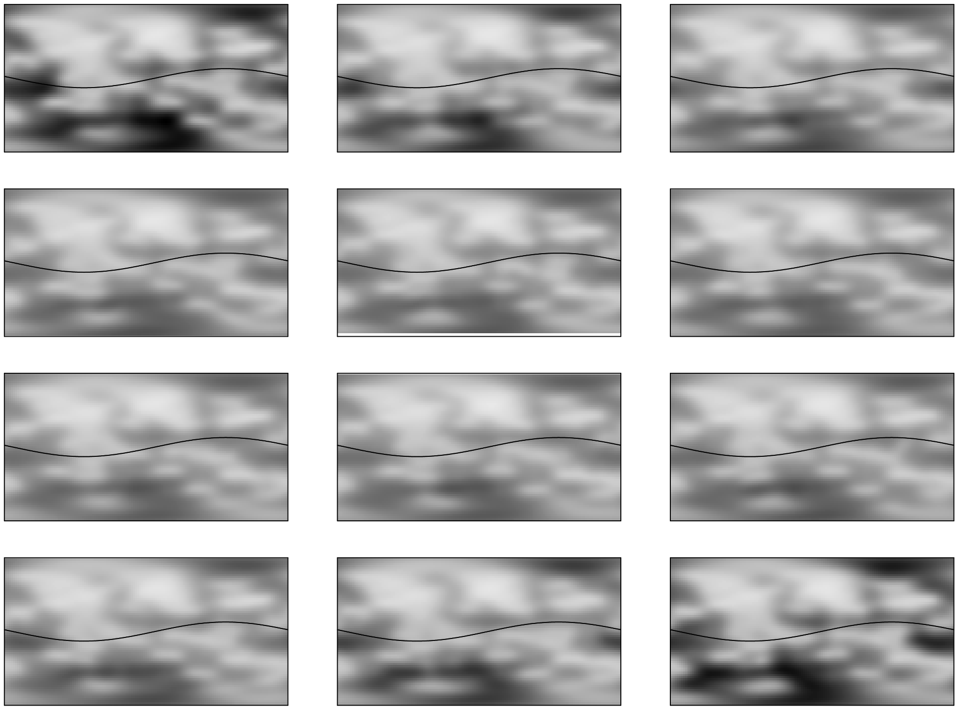
to the system of normal equations stemming from actual observations. Note that the a priori sigmas $\sigma_{\Delta e_{ij}}$ used for the pseudo-observations Δe_{ij} do not affect the “absolute” TEC determinations. Optimal values for these sigmas have to be found experimentally. Due to the fact that we deal with *normalized* SH coefficients, we may simplify this problem by setting $\sigma_{\Delta e_{ij}} \approx \sigma_{\Delta e}$.

A series of 12 2-hourly TEC maps (taken at 01:00, 03:00, …, 23:00 UT) is shown in Figure 8a. The typical double-peak structure co-rotating with the Sun fairly well follows the geomagnetic equator, even when referring the TEC representation to a solar-geographic coordinate system. Nevertheless, Figure 8a indicates that a solar-geomagnetic reference frame is more appropriate.

The associated RMS maps shown in Figure 8b describe the formal accuracy of the TEC as a function of earth-fixed coordinates and basically reflect the station coverage. “Light” regions indicate small RMS (see, e. g., Europe or North America), “dark” regions mean large RMS (see, e. g., the region around the station O’Higgens, Antarctica). The ratio of the largest and smallest RMS is about 11. Such RMS maps may be included in IONEX files [Schaer et al., 1998].



(a) TEC maps



(b) RMS maps

Figure 8. 2-hourly TEC and RMS maps for day 017, 1998

SUMMARY

The CODE Analysis Center produces global and European ionosphere maps by analyzing double-difference phase observations (using an interferometric processing technique) *and* phase-smoothed code observations (processing one-way observations) on a regular basis. Some changes were recently made in our processing scheme: The elevation cut-off angle was decreased from 20 to 10 degrees and at the same time the elevation-dependent observation weighting defining $\cos^2 z$ as weight on the zero-difference level, where z is the zenith distance, was activated. The maximum degree of the SH expansion was increased from 8 to 12 in order to be able to resolve smaller TEC structures like, e. g., the equatorial anomaly.

A higher temporal resolution when using SH expansions is possible by limiting the variations in time with slight "relative" constraints between consecutive sets of SH coefficients. The 2-hour results obtained are very encouraging. The higher the temporal resolution, the less important it is whether a solar-*geographic* or a solar-*geomagnetic* reference frame is used.

Daily sets of differential code biases for the GPS satellites (and receivers) are estimated at CODE since October 1997. The day-to-day scatter of the satellite-specific DCBs is about 0.08 ns. Finally, an approach based on a least-squares collocation to predict global TEC was developed. Approaching the next solar maximum, the knowledge of the ionosphere becomes more and more important. The access to *fast* and *up-to-date* ionospheric information is required by many applications.

OUTLOOK

We will start to produce global ionosphere maps with a 2-hour resolution in the near future. Furthermore we intend to derive predicted ionosphere maps on a regular basis (e. g., 2-day predictions).

The generation of global maps statistically describing the fluctuations of the TEC as presented in [Schaer et al., 1996b] is planned. Reprocessing all global data since 1995 becomes more and more important in view of the progress made in the ionosphere modeling.

It is our declared goal to continuously map the ionosphere for (at least) the next period of high solar activity and to study in particular the impact of the ionosphere on the IGS core products. The establishment of a future IGS ionosphere product as discussed at the IGS AC Workshop in Darmstadt, Germany [Feltens and Schaer, 1998] is another reason to continue these efforts.

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7 ANNEX C

7.1 KLOBUCHAR FILE FORMAT DESCRIPTION

IONEX: The IONosphere Map EXchange Format Version 1

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February 25, 1998

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.

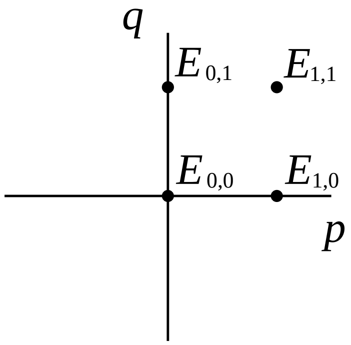

Figure 1: Bivariate interpolation using the nearest 4 TEC values $E_{i,j}$

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 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.	mI5
*RMS VALUES	RMS values are formatted exactly in the same way as TEC values (see above).	mI5 *
*HGT VALUES	HGT values are formatted exactly in the same 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'.	mI5 *

(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|
```