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IFMS Doppler 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

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1 INTRODUCTION

1.1 SCOPE

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

1.2 REFERENCED DOCUMENTS

	Reference Number	Title	Issue Number	Date
[1]	MEX-MRS-IGM-IS-3016	Radio Science File naming Convention	9.6	22.10.2004
[2]	IFMS_OCCFTP_10.5.0	IFMS-to-OCC	10.5.0	01.12.2004
[3]	MEX-MRS-IGM-DS-3039	Radio Science Predicted and Reconstructed Orbit Data: Specifications	2.3	17.05.2005
[4]	IFMS_SUM_10.3.1	Software User Manual	10.3.1	15.09.2004

1.3 DOCUMENT OVERVIEW

Section 2 defines the design specifications:
2.1 the input file names and used constants
2.2 defines MODULE PREDICT
2.3 defines MODULE DOPPLER

Section 3 gives an overview of the output file name definitions.
Section 4 describes the usage of the software and additional output files produced by means of a PERL script

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2 SOFTWARE DESIGN SPECIFICATIONS

2.1 MAIN PROGRAM SPECIFICATIONS

The MAIN program shall read the IFMS level 1a Doppler data both at S-band and X-band compute from the data contained therein the observed frequency received at groundstation. A detailed explanation of the computation is given in section 2.2. After reading the data the MAIN program shall correct the Doppler data for the contribution by the propagation through the plasma and the Earth troposphere. That step will be done via Module M_CALIBRATION. Doppler residuals will be computed from the predicted or reconstructed Doppler provided by M_PREDICT. The output data files and an log file containing processing information shall be produced via M_OUTPUT. The according label files shall be generated via M_LABEL.

2.1.1 <u>Modules</u>

The MAIN program uses a number of modules:

1. M_READ_INPUT_DATA
2. M_READ_HEADER
3. M_PREDICT
4. M_DOPPLER_SHIFT
5. M_CALIBRATION
6. M_IONO_CALIB
7. M_OUTPUT
8. M_DIFFERENTIAL DOPPLER
9. M_GLOBAL_VAR

and some general modules, wherein shared subroutines and functions are provided

10. M_FILE_UTILITIES
11. M_SPICE
12. M_ERROR
13. M_UTILITIES
14. M_FILE_NAMING_CONVENTION
15. M_LABELNAMEIFMS
16. M_LABEL
17. M_INTERPOL
18. M_SEARCH

The flow diagram is shown in section 2.1.4

2.1.2 Input files

2.1.2.1 Data file types

IFMS-SPEC-1210: the following table defines the input file types and the logical file names used in this specification and within the program.
Klobuchar coefficients are only needed if X-band and S-band Doppler files have no overlapping timestamp or the kind of data processing is occultation:

File type	Logical name within program
IFMS level 1a Doppler X-band S-band	 IFMS_DOPPLER_X IFMS_DOPPLER_S
predicted Doppler file	PREDICT_FILE
IFMS_Meteo file level 1a	IFMS_METEO
IFMS AGC file level 1a X-band S-band	IFMS_AGC_X IFMS_AGC_S
Klobuchar coefficients for Earth ionosphere calibration	ION_COEFF
Orbit SPICE Kernels	N/A

2.1.2.2 File names

IFMS-SPEC-1220: File names are defined in [1] section 4.1

2.1.2.3 File formats

IFMS-SPEC-1230: File formats are defined in [1] in section 5.2, section 8 and section 9

2.1.3 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-1025: PHYSICAL CONSTANTS

Constant		Value	SI units
Electron charge	e	$1.6022\ 10^{-19}$	A s
Electron mass	m_e	$9.1094\ 10^{-31}$	kg
Electric field constant	ε_0	$8.8542\ 10^{-12}$	$s^4\ A^2\ m^{-3}\ kg^{-1}$
Plasma constant	$\frac{1}{2}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}$	40.30924	$m^3\ s^{-2}$

IFMS-DEF-1030: CARRIER FREQUENCIES Mars Express (nominal)

Mars Express:

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

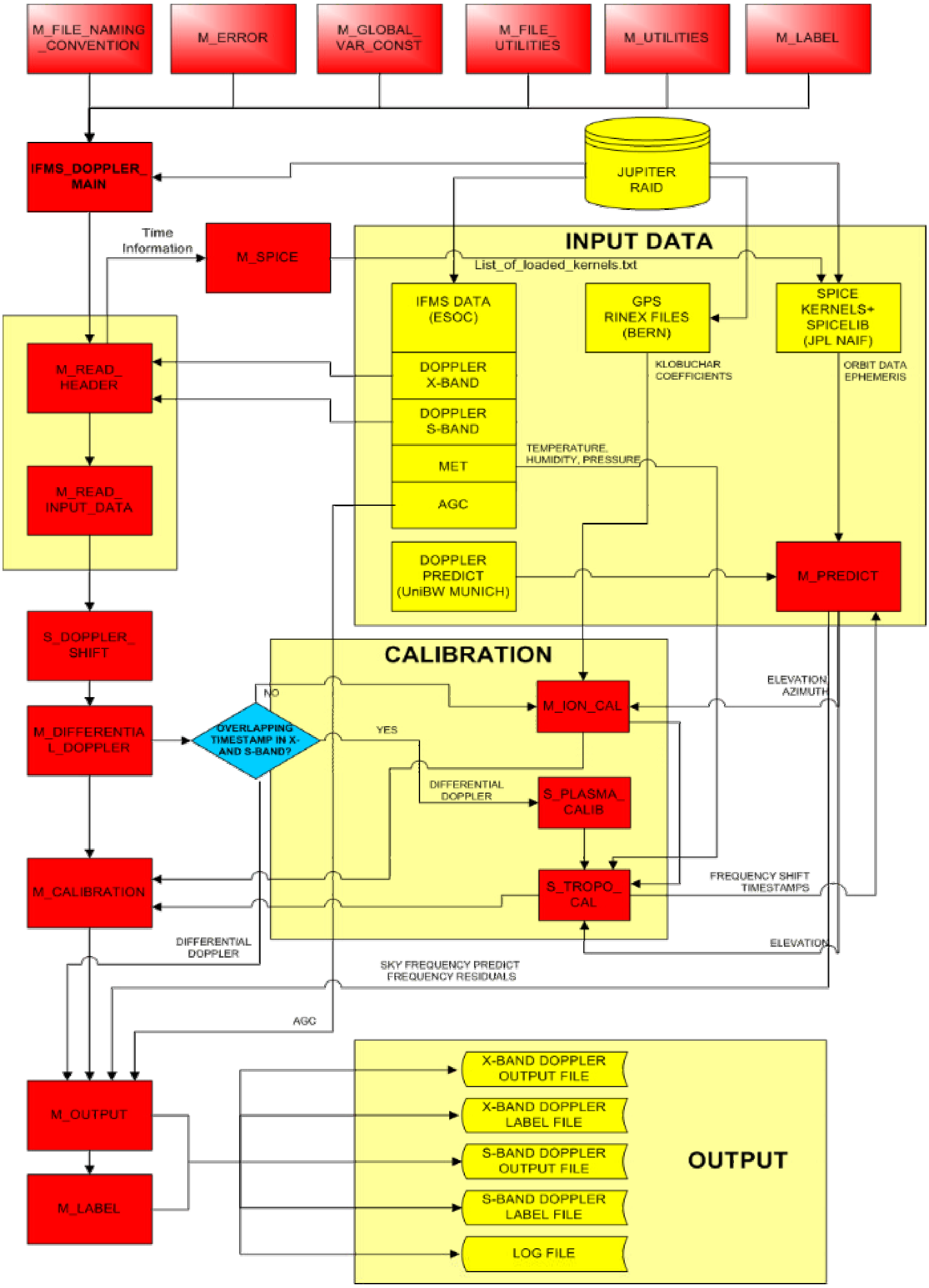
Actual transmitted frequencies (up and downlink) may vary according to expected Doppler shift (approx. 10 – 100 kHz).

IFMS-DEF-1031: Transponder 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

2.1.4 Flow Diagram



Figur 1: Flowchart for evaluation software for the IFMS Doppler data

2.2 MODULE M_READ_INPUT_DATA AND M_READ_HEADER

Module M_READ_HEADER contains subroutines in order to read the header and the active table from IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S.
Module M_READ_INPUT_DATA contains subroutines in order to read IFMS level 1a Doppler data at X-band and S-band, the meteorological data, the AGC data at X-band and S-band, respectively from IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S and to reconstruct the observed antenna frequency using therein contained data.
The main program is able to read more than one IFMS level 1a Doppler data at X-band and S-band, the meteorological data, the AGC data at X-band and S-band, respectively from IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S.

IFMS-SPEC-2305: M_READ_HEADER accepts the information contained in the header and active table of IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S.

IFMS-SPEC-2310: M_READ_INPUT_DATA accepts Doppler data from IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S.

IFMS-SPEC-2311: M_READ_INPUT_DATA merges Doppler data from IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S, if more than one respective IFMS level 1a file is available.

IFMS-SPEC-2315: The file name formats are defined according to [1] section 5.2.

IFMS-SPEC-2316: The file formats are defined according to [2] and [1] section 5.2.

IFMS-SPEC-2320: IFMS_DOPPLER_X, IFMS_DOPPLER_S, IFMS_METEO, IFMS_AGC_X and IFMS_AGC_S file names will be accepted via a Windows interface described in detail in section 4.1.

IFMS-SPEC-2321: The kind of data processing for (a) occultation entry, (b) occultation exit, (c) gravity, and (d) solar corona is selected via a graphical interface.

2.2.1 Computation of the observed antenna frequency

Subroutine S_READ_INPUT_DATA reads IFMS level 1a Doppler data at X-band and S-band and reconstructs the observed antenna frequency as followed using therein contained data. The required information contained in reads IFMS level 1a Doppler data at X-band and S-band for this computation are listed in detail in the above IFMS-DEF-2402. It is important to know that the timestamp in the original IFMS level 1a Doppler data is not the same as for the observed antenna frequency (see IFMS-SPEC-2401).

IFMS-SPEC-2400: antenna frequency $f_{antenna}$

$$\Delta count(t_i) = count(t_i) - count(t_{i-1})$$
$$\Delta time = \frac{\Delta count}{17.5x10^6}$$
$$\Delta phase(t_i) = phase(t_i) - phase(t_{i-1})$$
$$f_{offset,down} = k \cdot f_{offset,up}$$
$$\Delta phase_{Dop=0} = \Delta time \cdot f_{offset,down}$$
$$\Delta phase_{Dop}(t_i) = \Delta phase(t_i) - \Delta phase_{Dop=0}$$
$$f_{up} = f_{offset,up} + f_{\text{inter}} + f_{LO}$$
$$f_{antenna}(t_i) = k \cdot f_{up} + \frac{\Delta phase_{Dop}(t_i)}{\Delta time(t_i)}$$

For detailed information see in [2] section 6.3.

IFMS-SPEC-2401: The antenna frequency is computed between two time stamps t_i and t_{i+1} of the original IFMS level 1a Doppler data. Therefore the timestamp $t_{antenna}$ of the antenna frequency $f_{antenna}$ is computed via:

$$t_{antenna} = \frac{t_i + t_{i+1}}{2}$$

IFMS-DEF-2402: Definitions:

Acronyms as specified in [2]	Symbol	Explanation	SI units
Count	count($_{ti}$)	count at a given timestamp t_i	
DeltaCount	Δcount(t_i)	Variation of the counts of a numerical clock between two timestamps t_i and t_{i-1}, i.e nodes of the 17.5 MHz signal	
DeltaTime	Δtime	Time interval between two timestamps t_i and t_{i-1}	sec
Phase	phase(t_i)	measured phase in cycles	cycles
DeltaPhase	Δphase	Variation in phase between two timestamps t_i and t_{i-1} ,	cycles
ActualCarrierFreqOffset	$f_{offset,up}$	Expected uplink Doppler shift **Contained in ActiveTable**	Hz
InputCarrierFreqOffset	$f_{offset,down}$	expected uplink Doppler shift multiplied by the transponder ratio factor *k* defined in IFMS-DEF-1031; substracted from expected nominal uplink frequency received at spacecraft	Hz
ZeroDopplerDeltaPhase	$\Delta phase_{Dop=0}$	Phase change in Δtime assuming that Doppler shift is zero	cycles
DeltaPhaseDoppler	$\Delta phase_{Dop}$	Phase change in Δtime for the true Doppler shift	cycles
UlmCarFrSel	f_{inter}	Intermediate frequency after downconversion Ca. 70 MHz or 230 MHz **Contained in ActiveTable**	Hz
XxxUplkConv	f_{LO}	Ground station local oscillator frequency in order to generate true uplink frequency Ca. 7100 MHz or 2100 MHz **Contained in ActiveTable**	Hz
UplinkCarrierFreq	f_{up}	transmitted uplink carrier frequency	Hz

IFMS-SPEC-2403: The uplink frequency f_{up} (result from IFMS-SPEC-2401) is transferred to M_OUTPUT and stored in column 7.

IFMS-SPEC-2404: Column 8 in M_OUTPUT (uplink frequency ramp rate) is set to zero.

IFMS-SPEC-2405: The antenna frequency $f_{antenna}$ (result from IFMS-SPEC-2401) is transferred to M_OUTPUT and stored in column 9.

2.3 MODULE M_SPICE

The IFMS Doppler Processing Software uses the program package SPICE built by the Navigation and Ancillary Information Facility (NAIF) at the Jet Propulsion Laboratory. The SPICE system includes a large suite of software, mostly in the form of subroutines to compute derived observation geometry and to perform other useful computations. The SPICE system needs so called kernels containing information for example about Spacecraft ephemeris as a function of time. For more information about SPICE see

http://naif.jpl.nasa.gov/naif/.

Module M_SPICE provides a subroutine S_WRITE_LOLK in order to generate a file which comprises a list of kernels to load for the SPICE system. The name of the generated file is “list_of_loaded_kernels.txt” and contains all files required to perform the processing step. The selection of the kernels depends on mission, time of the operation and receiving groundstation. An example of such a file is given in Figure 2-1.
The file containing the required kernels is automatically generated in the subdirectory \kernels of the directory where the IFMS Doppler Processing Software is located. The required kernels have to be located also in the subdirectory \kernels.

Figure 2-1: Example of file „list_of_loaded_kernels,txt”

```
\begindata
KERNELS_TO_LOAD = (
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\PCK00008.TPC',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\EARTH_000101_050131_04110
9.BPC',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\earthfixedITRF93.frm',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\earthfixedIAU.frm',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\new_norcia.txt',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\new_norcia.bsp',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\new_norcia_topo.frm',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\mars_iau2000_v0.tpc',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\MEX_040930_STEP.TSC',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\ORMM__041001000000_00096.
BSP',
'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\de405s.bsp'
)
```

2.4 MODULES M_CALIBRATION AND M_IONO_CALIB

Module M_CALIBRATION provides several subroutines in order to correct for the contribution by the propagation through the plasma and the neutral Earth troposphere.
Module M_IONO_CALIB provides several subroutines to compute the correction for the Earth ionosphere, i.e. the ionospheric delay in nanoseconds, using the so called Klobuchar model for the Earth ionosphere.
Plasma media correction can only be performed if two downlink frequencies have been recorded and is done only for gravity observations. If only one frequency is available or for occultation observations, the Earth ionosphere is corrected via the Klobuchar model.

2.4.1 Tropospheric calibration

Subroutine S_TROP_CALIB uses the meteo data observed at the respective ground station to compute the path delay (unit is meter) of the dry and wet component of the Earth troposphere and calculate from the path delay the total correction for the Earth troposphere in Hz.

IFMS-SPEC-2460: 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.):

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

$$\Delta_{wet}(E) = \frac{10^{-6}}{5} \frac{-12.96T+3.718\cdot 10^5}{\sin\left(\sqrt{E^2+2.25}\right)}\frac{e}{T^2}11000 \qquad (1.1)$$

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:

$$e = 6.108 \cdot 10^{-2} \cdot humidity[\%] \cdot \exp\left\{\frac{17.393(T - 272.15)}{T - 33.95}\right\} \qquad (1.2)$$

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

$$t_{tropo} = \frac{2}{c}\left\{\Delta_{dry}(E) + \Delta_{wet}(E)\right\} \qquad (1.3)$$

for the two-way radio link where c is the speed of light with definition given in IFMS-DEF-1020 and

$$t_{tropo} = \frac{1}{c}\left\{\Delta_{dry}(E) + \Delta_{wet}(E)\right\}$$

for the one-way radio link.

IFMS-SPEC-2461: The correction for the Earth troposphere is then for one-way radio link:

$$m_{ONE} = t_{tropo} \cdot f_{down} \qquad (1.4)$$

and for the two-way radio link:

$$m_{TWO} = t_{tropo} \cdot \left(f_{down} + f_{up}\right) \qquad (1.5)$$

where m is the cycle advance and the shift in frequency is:

$$\Delta f_{ONE,tropo} = \frac{dm_{ONE}}{dt} \qquad (1.6)$$

and for the two-way radio link:

$$\Delta f_{TWO,tropo} = \frac{dm_{TWO}}{dt} \qquad (1.7)$$

This is done for each frequency band.

IFMS-SPEC-2462: The result from IFMS-SPEC-2461 is transferred to M_OUTPUT, added to the respective plasma correction described below and the sum is stored in column 11.

IFMS-SPEC-2463: The result from IFMS-SPEC-2461 is transferred to M_PREDICT and added to the predicted Doppler data (see section 2.5)

2.4.2 <u>Differential Doppler</u>

Subroutine S_DIFF_DOP finds out whether IFMS level 1a Doppler data at X-band and S-band are overlapping in time. If this is the case and the IFMS level 1a Doppler data at X-band and S-band having the same sample interval the differential Doppler is computed.

IFMS-SPEC-2465: <u>Differential Doppler</u>
The result from IFMS-SPEC-2363 is taken to compute the differential Doppler

$$d\,f = f_{S,antenna} - \frac{3}{11} f_{X,antenna} \tag{1.8}$$

IFMS-SPEC-2466: The result from IFMS-SPEC-2465 is transferred to M_OUTPUT and stored in column 14.

2.4.3 <u>Plasma calibration using the differential doppler</u>

Subroutine S_PLASMA_CALIB calculates the temporal change in electron content from the differential Doppler and the according frequency-shift in antenna frequency at X-band and S-band

IFMS-SPEC-2470: <u>Plasma calibration</u>
Derive the temporal change in electron content from the differential Doppler and computes the dispersive frequency shift for each frequency band. f_S and f_X are downlink carrier frequencies and c is the speed of light, all defined in section 1.

$$\begin{aligned} df &= -\frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\} f_S \frac{dI}{dt} \\ \Rightarrow \frac{dI}{dt} &= -\left\{\frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\right\}^{-1} \frac{df}{f_S}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\}^{-1} \end{aligned} \tag{1.9}$$

IFMS-SPEC-2471: <u>plasma correction</u>
The temporal change in electron content will be used to correct for the downlink plasma propagation for gravity observations only:

$$\begin{aligned} \Delta f_{S,plasmacal} &= \frac{40.31}{c}\frac{1}{f_S}\frac{dI}{dt} \\ \Delta f_{X,plasmacal} &= \frac{40.31}{c}\frac{1}{f_X}\frac{dI}{dt} \end{aligned} \tag{1.10}$$

If equation (1.9) is applied to equation (1.10), the plasma correction is than

$$\Delta f_{S,plasma,cal} = df\,\frac{121}{112}$$
$$\Delta f_{X,plasma,cal} = df\,\frac{33}{112} \qquad (1.11)$$

For further details see APPENDIX B

IFMS-SPEC-2472: The result from IFMS-SPEC-2471 is transferred to M_OUTPUT added to the tropospheric correction described above and the sum is stored in column 11

IFMS-SPEC-2473: The result from IFMS-SPEC-2471 is transferred to M_PREDICT and added to the predicted Doppler data (see section 2.5)

2.4.4 Plasma calibration using the Klobuchar model

If only one frequency is available or the kind of data processing is Occultation, the Earth ionosphere plasma has to be modeled. Module M_IONO_CAL contains subroutines in order to provide a model of the electron content of the Earth ionosphere and will be described below in detail.

2.4.4.1 The Klobuchar model

Module M_IONO_CALIB contains several subroutines to provide a model of 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_CALIB 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.

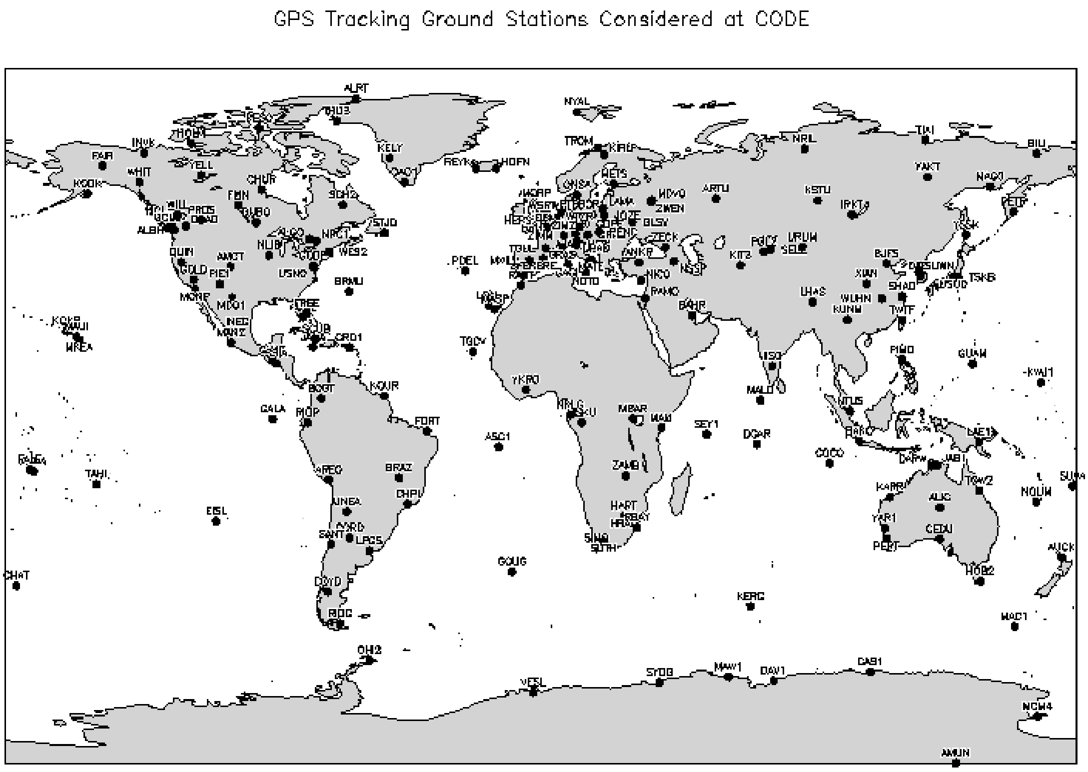


Figure 2-2: GPS Tracking Ground Stations

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-2480: Module M_IONO_CALIB 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_CALIB 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	

Table 2-1: Input parameter of M_IONO_CALIB

IFMS-SPEC-2481: The output of Module M_IONO_CALIB is the ionospheric slant range correction τ_{iono}. The unit of τ_{iono} is seconds. The calculation of τ_{iono} is described in IFMS-SPEC-2482**.**

IFMS-SPEC-2482: The computation of the ionospheric slant range correction t_{iono} depends on the local time at the ground station side. For the calculation of t_{iono} the following parameters are used:

1. **Local Time t:**

$$t = 4.32 \cdot long\_i + TOW$$

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. · (0.53-e)^3 !

9. **Period of model PER:**

   If PER less than 72000.D0

   PER = 72000.

   Else

   PER = beta(1) + beta(2) ·lat_m + beta(3) ·lat_m^2 +beta(4) ·lat_m^3

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

    x = 2.·pi·(t-50400.) / PER !

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

    AMP = alpha (1) + alpha (2) ·lat_m + alpha (3) ·lat_m^2 +alpha(4) ·lat_m^3

12. **Ionospheric slant correction** t_{iono}**:**

Night (DABS(x) greater Than 1.57):

τ_{iono} = sf · (5.D-9)

Day:

τ_{iono} = sf · (5.D-9 + AMP*(1.D0 – x^2/2. + x^4/24.))

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.

2.4.4.2 Plasma calibration of the antenna frequency

Subroutine S_PLASMA_CALIB_MOD corrects for the contribution by the propagation through the earth ionosphere by using the model for the earth ionosphere defined in module M_ION_CALIB.

IFMS-SPEC-2483: Subroutine S_PLASMA_CALIB_MOD accepts the ionospheric slant correction τ_{iono} from module M_IONO_CALIB

IFMS-SPEC-2484: The correction for the Earth ionosphere is then

$$m = t_{iono} \cdot f_{down}$$

where *m* is the cycle advance and the shift in frequency is:

$$\Delta f_{iono} = \frac{dm}{dt_{iono}}$$

This is done for each frequency band
.
IFMS-SPEC-2485: The result from IFMS-SPEC-2484 is transferred to M_OUTPUT added to the tropospheric correction described above and the sum is stored in column 11

IFMS-SPEC-2486: The result from IFMS-SPEC-2484 is transferred to M_PREDICT and added to the predicted Doppler data (see section 2.5)

2.5 MODULE M_PREDICT

M_PREDICT accepts a Doppler predict file: the predict file PREDICT_FILE considers all possible perturbing forces as the best known gravity field and solar and albedo radiation pressure. For more details about the PREDICT_FILE see document [3]. M_PREDICT interpolates for a given time stamp between the computed sky frequency based on predicted parameters and returns an estimated sky frequency for each observed time stamp. This is done for each frequency band.

IFMS-SPEC-2510: M_PREDICT accepts input data from PREDICT_FILE with the file name format defined in [1] section 8.1 or in [1] section 8.2 for the predicted orbit or the reconstructed orbit file, respectively. PREDICT_FILE contains both the Doppler uplink and downlink data.

IFMS-SPEC-2520: M_PREDICT accepts predicted Doppler data from PREDICT_FILE (file name specified in IFMS-SPEC-2210) formatted as defined in [1] section 8.1 or in [1] section 8.2 for the predicted orbit or the reconstructed orbit file, respectively.

IFMS-SPEC-2525: M_PREDICT_FILE contains predicted Doppler data with a time period that covers one entire operation.

IFMS-SPEC-2530: Subroutine S_DOP_PRED reads predicted Doppler data from PREDICT_FILE and computes for each frequency band the predicted antenna frequency $f_{pred,antenna}$ received at a given ground station via

$$f_{pred,antenna} = k \cdot f_{up} \left(1 + P_{up} + P_{down} + P_{up} \cdot P_{down}\right)$$

where $P_{up} = \frac{\Delta f_{up}}{f_{up}} = \frac{v_{r,up}}{c}$ and P_{down} is the predicted Doppler of the uplink and the downlink path, respectively. The result is stored in the array DOPPLER_PREDICT_SKY. For more details about the computation see Appendix A.

IFMS-SPEC-2535: Subroutine S_DOP_PRED accepts from M_READ_INPUT_DATA the array TIME_DOPPLER representing the observed Doppler time stamps. S_DOP_PRED interpolates between each sky frequency data of DOPPLER_PREDICT_SKY for each observed time stamp given as TIME_DOPPLER. This is done for each frequency band.

IFMS-SPEC-2540: The interpolated result will be provided as the array DOPPLER_PREDICT_INT in subroutine S_DOP_PRED. The troposheric calibration and the plasma correction are added to the interpolated predicts.

$$f_{pred,calib} = f_{pred} + \Delta f_{iono} + \Delta f_{tropo}$$

This is done for each frequency band.

IFMS-SPEC-2545: The corrected result from IFMS-SPEC-2540 will be provided as the array DOPPLER_PREDICT_CAL in subroutine S_DOP_PRED. The array is transferred to the subroutine M_OUTPUT and stored in column 10 of the output file. This is done for each frequency band.

IFMS-SPEC-2550: Subroutine S_DOP_PRED computes for each frequency band the frequency residuals Δf_{res} by subtracting the interpolated and corrected, predicted antenna frequency $\Delta f_{predcalib}$ stored in the array DOPPLER_PREDICT_INT from the measured and calibrated antenna frequency $f_{antenna}$.

$$\Delta f_{res} = f_{antenna} - f_{pred,calib}$$

IFMS-SPEC-2551: The result from IFMS-SPEC-2550 is transferred to M_OUTPUT and stored in column 12.

IFMS-SPEC-2560: M Subroutine S_DOP_PRED reads time values of the two way light time from PREDICT_FILE and interpolates between each value of the two way light time for each observed time stamp given as TIME_DOPPLER. This is done for each frequency band.

IFMS-SPEC-2561: The resulting values are subtracted from TIME_DOPPLER at each time stamp in order to compute the transmit frequency ramp reference time.

IFMS-SPEC-2562: The result from IFMS-SPEC-2561 is transferred to M_OUTPUT and stored in column 6.

3 OUTPUT FILES

3.1 MODULE M_OUTPUT

The module M_OUTPUT provides different functions and subroutines in order to generate the output files of the X-band and S-band Doppler data. In addition routines are provided to produce the .log file and a file containing data about frequency computation if the information in the header and the active table of the IFMS X-band and S-band files are not equal.

3.1.1 Data files

IFMS-SPEC-3000: The DOPPLER_OUTPUT file names are defined as

rggICLxL02_sss_yydddhhmm_qq.TAB

The definitions are given in Table 3-1.

Table 3-1: DOPPLER_OUTPUT file name Definition

placeholder	description	example
r	spacecraft name M = MEX R = Rosetta V = VEX	M
gg	ground station xx = ESA Cerbreros 32 = ESA New Norcia	32
ICLx	Data source IFMS closed-loop x = 1 => NN11 x = 2 => NN12 x = 3 => NN13	ICL1
L02	Data level L02	L02
sss	File type D1X = X-band Doppler file channel 1 D1S = S-band Doppler file channel 1 D2X = X-band Doppler file channel 2 D2S = S-band Doppler file channel 2	D1X
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

IFMS-SPEC-3010: The format of the DOPPLER_OUTPUT_X file is defined in Table 3-2. The format of the DOPPLER_OUTPUT_S file is defined in Table 3-3.

IFMS-SPEC-3020: All data that are not available in the data file are set to a default value corresponding to their format description. For example data with format F10.3 are set to -99999.999. This default value indicates that the data is not a valid number and can not be used for further computations. For details see Table 3-2 and Table 3-3.

IFMS-SPEC-3030: The first and the last value of column 11 of the DOPPLER_OUTPUT_X file and DOPPLER_OUTPUT_S_file (calibration) is set to his default value due to the way of computation.

IFMS-SPEC-3040: If the differential Doppler can not be computed the differential Doppler will be set to -99999.999. This is the case if only X-band Doppler data exist, only S-band Doppler data exist and/or the sample interval of S-Band data and X-Band data are not equal.

Table 3-2 Definition of DOPPLER_OUTPUT_X file format

column	description	unit	resolution
1	Sample number		
2	Ground received time *as UTC in ISO format*		
3	Ground received time *as UTC in fractions of day of year starting with the first day of the year the data was recorded at 00:00.000*	days	10^{-10} days
4	Ground received time *as elapsed terrestrial barycentric dynamic time (TDB) time since noon of the first calendar day of year 2000 (12:00 1 January 2000 TDB)*	sec	10^{-6} sec
5	Geometric impact parameter *<u>Propagation experiments:</u> approximate value of the closest approach of a downlink geometric ray path to the center of the reference body (Sun, planet, minor object). When two-way, the value is approximate average of uplink and downlink rays* *<u>Gravity observations:</u> geometric distance of the s/c from the center of mass of referenced body*	km	10^{-3} m
6	Transmit frequency ramp reference time *UTC in ISO format* *The time (t0) at which the transmitted frequency would have been f_0 using the coefficients f_0 (column 7) and df (column 8). At any time t within the interval when those coefficients are valid, the transmitted frequency f_t may* *be calculated from* $f_t = f_0 + df \cdot (t - t_0)$ *<u>For DSN two-way measurements:</u>* *f_t is the uplink frequency of the ground transmitter; the f_t photon will reach the receiver one RTLT later.* *<u>For DSN one-way measurements</u>:* *f_t is the downlink frequency of the spacecraft transmitter; the f_t photon will reach the receiver OWLT later. In both cases, f_0 and df may change; but f_t is always continuous, and changes in the coefficients occur only on integer seconds.* *<u>For IFMS measurements:</u>* $f_t = f_0$ *because df=0.*		

7	Transmit frequency corresponding to time in column 6 *<u>Two-way coherent modes:</u>* *Uplink frequency of ground station* *S-band order of 2100 MHZ* *X-band order of 7100 MHz* *<u>One-way mode:</u>* *S/C transmission frequency* *X-band order of 8400 MHz* *S-band order of 2300 MHz*	Hz	10^{-6} Hz
8	Uplink frequency ramp rate *<u>DSN two-way coherent:</u>* *Time derivative of uplink frequency in column 7* *<u>DSN one-way downlink mode:</u>* *Value of spacecraft frequency drift, if known and/or meaningful; -99999.999999* *<u>IFMS measurements:</u>* *Ramp rate is always zero; df=0*	Hz/sec	10^{-6} Hz/sec
9	Observed X-band antenna frequency *Frequency of the signal at the terminals of the receiving antenna structure at UTC TIME columns 2 to 4 (t_r). Set to -9999999999.999999 for missing or corrupted data.*	Hz	10^{-6} Hz
10	Predicted X-band antenna frequency *Based on the ESOC reconstructed orbit file or SPICE kernels* *Expected frequency of the signal at the terminals of the receiving antenna structure at UTC TIME in columns 2 to 4 (t_r). The calculation includes geometrical effects (relative positions and motions of ground station and spacecraft, including Earth rotation and light time adjustments), tuning of both the transmitter and receiver and a model-based correction for one- or two-way (as appropriate) propagation through the Earth's atmosphere.*	Hz	10^{-6} Hz
11	Correction of Earth atmosphere propagation Correction term for the propagation of the signal in the Earth atmosphere, based on meteorological data observed at the ground station site (MET-files)	Hz	10^{-6} Hz
12	Residual calibrated X-band frequency shift *column 9 minus 10*	Hz	10^{-6} Hz
13	Received signal level *<u>Closed-loop data:</u>* *Signal level from AGC in decibels relative*	dBm / dB	0.1 dB

	to one milliwatt (dBm). *<u>Open-loop (RSR):</u>* *Signal level in decibels (dB) relative to an arbitrary reference.*		
14	Differential Doppler $$f_S - \frac{3}{11} f_X$$ *Where f_S and f_X are the received S-band and X-band frequencies* *If* BAND_NAME = X *(from the label file), f_X comes from column 9 in this table and f_S comes from column 9 in the file identified by* SOURCE_ID *(from the label file).* *If* BAND_NAME = S *(from the label file), f_S comes from column 9 in this table and f_X comes from column 9 in the file identified by* SOURCE_ID *(from the label file).* *if either band is not available, this column is set "-99999.999"*	Hz	10^{-6} Hz
15	standard deviation of the observed antenna frequency X-band in column 9 (open-loop only) *for closed-loop this value is set "-99999.999"*	Hz	10^{-6} Hz
16	Received X-band signal quality (open-loop only) *Ratio of observed received signal strength to the statistical standard deviation of the measurement, column 15 devided by column 19* *For closed-loop this is value is set "-999.9"*	dB	0.1 dB
17	standard deviation of received signal level at X-band (open-loop) *A statistical measure of the error in determining SIGNAL LEVEL (column 15) based on fit of a data spectrum to a sinc function. Uses the same arbitrary scale factor as column 15; units of dB.* *for closed-loop this is set "-999.9"*	dB	0.1 dB

Table 3-3: Definition of DOPPLER_OUTPUT_S file format

column	description	unit	resolution
1	Sample number		
2	Ground received time *as UTC in ISO format*		
3	Ground received time *as UTC in fractions of day of year starting with the first day of the year the data was recorded at 00:00.000*	days	10^{-10} days
4	Ground received time *as elapsed terrestrial barycentric dynamic time (TDB) time since noon of the first calendar day of year 2000 (12:00 1 January 2000 TDB)*	sec	10^{-6} sec
5	Geometric impact parameter <u>Propagation experiments:</u> *approximate value of the closest approach of a downlink geometric ray path to the center of the reference body (Sun, planet, minor object). When two-way, the value is approximate average of uplink and downlink rays* <u>Gravity observations:</u> *geometric distance of the s/c from the center of mass of referenced body*	km	10^{-3} m
6	Transmit frequency ramp reference time *UTC in ISO format* *The time (t0) at which the transmitted frequency would have been f_0 using the coefficients f_0 (column 7) and df (column 8). At any time t within the interval when those coefficients are valid, the transmitted frequency f_t may be calculated from* $$f_t = f_0 + df \cdot (t - t_0)$$ <u>*For DSN two-way measurements:*</u> *f_t is the uplink frequency of the ground transmitter; the f_t photon will reach the receiver one RTLT later.* <u>*For DSN one-way measurements*</u>*:* *f_t is the downlink frequency of the spacecraft transmitter; the f_t photon will reach the receiver OWLT later. In both cases, f_0 and df may change; but f_t is always continuous, and changes in the coefficients occur only on integer seconds.* <u>*For IFMS measurements:*</u> $$f_t = f_0$$ *because df=0.*		

7	Transmitted frequency corresponding to time in column 6 *<u>Two-way coherent modes:</u>* *Uplink frequency of ground station* *S-band order of 2100 MHZ* *X-band order of 7100 MHz* *<u>One-way mode:</u>* *S/C transmission frequency* *X-band order of 8400 MHz* *S-band order of 2300 MHz*	Hz	10^{-6} Hz
8	Uplink frequency ramp rate *<u>DSN two-way coherent:</u>* *Time derivative of uplink frequency in column 7* *<u>DSN one-way downlink mode:</u>* *Value of spacecraft frequency drift, if known and/or meaningful; -99999.999999* *<u>IFMS measurements:</u>* *Ramp rate is always zero; df=0*	Hz/sec	10^{-6} Hz/sec
9	Observed S-band antenna frequency *Frequency of the signal at the terminals of the receiving antenna structure at UTC TIME columns 2 to 4 (t_r). Set to -9999999999.999999 for missing or corrupted data.*	Hz	10^{-6} Hz
10	Predicted S-band antenna frequency *Based on the ESOC reconstructed orbit file or SPICE kernels* *Expected frequency of the signal at the terminals of the receiving antenna structure at UTC TIME in columns 2 to 4 (t_r). The calculation includes geometrical effects (relative positions and motions of ground station and spacecraft, including Earth rotation and light time adjustments), tuning of both the transmitter and receiver and a model-based correction for one- or two-way (as appropriate) propagation through the Earth's atmosphere.*	Hz	10^{-6} Hz
11	Correction of Earth atmosphere propagation *Correction term for the propagation of the signal in the Earth atmosphere and ionosphere, based on meteorological data observed at the ground station site (MET-files)*	Hz	10^{-6} Hz
12	Residual calibrated X-band frequency shift *column 9 minus 10*	Hz	10^{-6} Hz
13	Received S-band signal level	dBm /	0.1 dB

	<u>Closed-loop data:</u> *Signal level from AGC in decibels relative to one milliwatt (dBm).* *<u>Open-loop (RSR):</u>* *Signal level in decibels (dB) relative to an arbitrary reference.*	dB	
14	Differential Doppler $f_S - \frac{3}{11} f_X$ *Where f_S and f_X are the received S-band and X-band frequencies* *If* BAND_NAME = X *(from the label file),* f_X *comes from column 9 in this table and* f_S *comes from column 9 in the file identified by* SOURCE_ID *(from the label file).* *If* BAND_NAME = S *(from the label file),* f_S *comes from column 9 in this table and* f_X *comes from column 9 in the file identified by* SOURCE_ID *(from the label file).* *if either band is not available, this column is set "-99999.999"*	Hz	10^{-6} Hz
15	standard deviation of the observed antenna frequency S-band in column 9 (open-loop only) *for closed-loop this value is set "-99999.999"*	Hz	10^{-6} Hz
16	Received S-band signal quality (open-loop only) *Ratio of observed received signal strength to the statistical standard deviation of the measurement, column 15 devided by column 19* *For closed-loop this is value is set "-999.9"*	dB	0.1 dB
17	standard deviation of received signal level at S-band (open-loop) *A statistical measure of the error in determining SIGNAL LEVEL (column 15) based on fit of a data spectrum to a sinc function. Uses the same arbitrary scale factor as column 15; units of dB.* *for closed-loop this is set "-999.9"*	dB	0.1 dB

3.1.2 Label files

See [1] for more information.

3.1.3 Additional Output Files

3.1.3.1 Log file

The Module M_OUTPUT generates an additional output file a so called log file. This file contains the processing mode, the whole path of all input files, additional information like downlink and uplink frequency in Hz, the sample rate in samples per seconds, statistical data about the processed data like average value and standard deviation, version of the processing software and error messages.
The log file will not be distributed and is only intended for internal use. Therefore the filename of the log file is not complying with [1]. But in order to relate the log file with the corresponding data files the log file gets the file name of the corresponding DOPPLER_OUTPUT_X_file but instead of the ending .tab the ending .log is used. If a log file is already existing in the processing folder and the date are not automatically processed the log file gets the file name of the corresponding DOPPLER_OUTPUT_S_file with ending .log. An example of a log file is shown in Figure 3-1.

IFMS-SPEC-3100: The average values of the residuals of S-Band data and X-Band data are computed only for the first 40% of the data. The computation is done via the following formulation

$$\overline{f}_{res} = \frac{1}{N}\sum_{i=1}^{N} f_{res_i}$$

IFMS-SPEC-3110: The standard deviation of the residuals of S-Band data and X-Band data are computed only for the first 40% of the data. The computation is done via the following formulation

$$f_{res,std} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_{res_i} - \overline{f}_{res}\right)^2}$$

```
MEX

GR

GRAVITY

FLAGS FROM PROCESS_OPTIONS FILE:
--------------------------------
T     Processing with Predict
T     Processing with AGC
F     Additional file containing the correct frequencies is needed
T     Active table of the X-band file contains the correct frequencies
F     Coherency flag is automatically set to false (i.e. one-way)

NUMBER OF INPUT FILES:
----------------------
02     Number of doppler S-band files
02     Number of doppler X-band files
01     Number of Meteo files
02     Number of AGC S-Band files
02     Number of AGC X-Band files

FILES USED FOR PROCESSING:
--------------------------
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN13_MEX1_20
05_002_OP_D1_054220_0000
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN13_MEX1_20
05_002_OP_D1_054220_0001
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN11_MEX1_20
05_002_OP_D1_054206_0000
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN11_MEX1_20
05_002_OP_D1_054206_0001
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\add\NN11_MEX1_2005_002_OP
_ME_054214_0000
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\add\M32UNBWL02_PTW_050020
523_00.TAB
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN13_MEX1_20
05_002_OP_G1_054232_0000
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN13_MEX1_20
05_002_OP_G1_054232_0001
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN11_MEX1_20
05_002_OP_G1_054218_0000
Z:\processed_temp\mex\Orbit\2005\DOY_002_1_MEX\NN13_NN11\D1\NN11_MEX1_20
05_002_OP_G1_054218_0001
```

```
FILES CREATED DURING PROCESSING:
--------------------------------
Z:/Processed_temp/MEX/Orbit/2005/DOY_002_1_MEX/NN13_NN11/D1/M32ICL3L02
_D1S_050020542_00.TAB
Z:/Processed_temp/MEX/Orbit/2005/DOY_002_1_MEX/NN13_NN11/D1/M32ICL1L02
_D1X_050020542_00.TAB
Z:/Processed_temp/MEX/Orbit/2005/DOY_002_1_MEX/NN13_NN11/D1/M32ICL3L02
_D1S_050020542_00.LBL
Z:/Processed_temp/MEX/Orbit/2005/DOY_002_1_MEX/NN13_NN11/D1/M32ICL1L02
_D1X_050020542_00.LBL

CONFIGURATION INFO:
--------------------
UPLINK-FREQUENCY X-BAND:   7166619369.9976720809936523
DOWNLINK-FREQUENCY X-BAND:   8420060140.9852495193481445
SAMPLE-INTERVAL X-BAND:            1.0000000000000000
TRANSPONDER-RATIO X-BAND:880/749
UPLINK-FREQUENCY S-BAND:   7166619369.9976720809936523
DOWNLINK-FREQUENCY S-BAND:   2296380038.4505224227905273
SAMPLE-INTERVAL S-BAND:            1.0000000000000000
TRANSPONDER-RATIO S-BAND:240/749

PROCESSING INFO
 ---------------
AVERAGE S-BAND RESIDUALS IN mHZ:            -6.94218
STANDARD DEVIATION S-BAND RESIDUALS IN mHZ:            4.39143
AVERAGE X-BAND RESIDUALS IN mHZ:             9.68471
STANDARD DEVIATION X-BAND RESIDUALS IN mHZ:           14.90616
PLASMA-CORRECTION DONE WITH DIFFERENTIAL DOPPLER
FILES OVERLAPPING IN TIME
X-BAND-MODE: TWO-WAY
S-BAND-MODE: TWO-WAY

SOFTWARE INFO:
--------------
SOFTWARE NAME: ESA_IFMS_PROC_DOP_L1A_TO_L2_V2.0
CREATION TIME: 2005-05-27T12:23:41.000
PROCESSED BY: andert

ERRORS:
 -------
```

Figure 3-1: Example of a log file

3.1.3.2 Frequency correction files

The data contained in the header and active table of the IFMS level 1a Doppler data file at X-band and S-band for reconstruction of the uplink frequency at groundstation should be equal because only one signal with one frequency is emitted from groundstation.
Sometimes the data for frequency reconstruction IFMS level 1a Doppler data file at X-band and S-band are not equal due to unknown problems on ESOC site. In this case the data for frequency reconstruction of the IFMS level 1a Doppler data file are used per default from the IFMS level 1a Doppler data file at X-band for processing both files and a data file containing information about the source file, the output file, the file in which the frequency is changed and the original and new frequency and the according label file is generated.

IFMS-SPEC-3150: The UPLINK_CORRECTION and the according label file names are defined as

UPLINK_FREQ_CORRECT_NN nn_Dd.eee

Acronym	Description	Example
nn	IFMS 1, 2 or 3	NN11 NN12 NN13
d	Doppler channel 1 or 2	1 2
eee	File ending	TAB (Data file) LBL (Label file)

Table 3-4: File Naming Convention of the uplink frequency correction file and the corresponding label file.

Table 3-5 Definition of **UPLINK_CORRECTION** file format

column	description
1	Original Level 1a file in which the wrong frequency information are detected
2	Level 2 file in which the corrected frequency information are incorporated
3	Original uplink frequency [Hz]
4	Corrected uplink frequency [Hz]
5	Source file where the correct frequency is stored

A detailed description of the label files can be found in [1] .

4 USAGE OF THE SOFTWARE

The above described software is embedded in a PERL script that calls the software. The processing options like mission, observation type and number of files can be adjusted by means of a graphical interface. In addition there is a possibility provided to process an amount of data automatically. But for this a log file (see section 3.1.3.1) must exist.

The selection of the respective files for processing is done via another graphical interface shown below in Figure 4-1. The simultaneously arising DOS window (see Figure 4-2) indicates what kind of file is needed and shows subsequently the processing status.

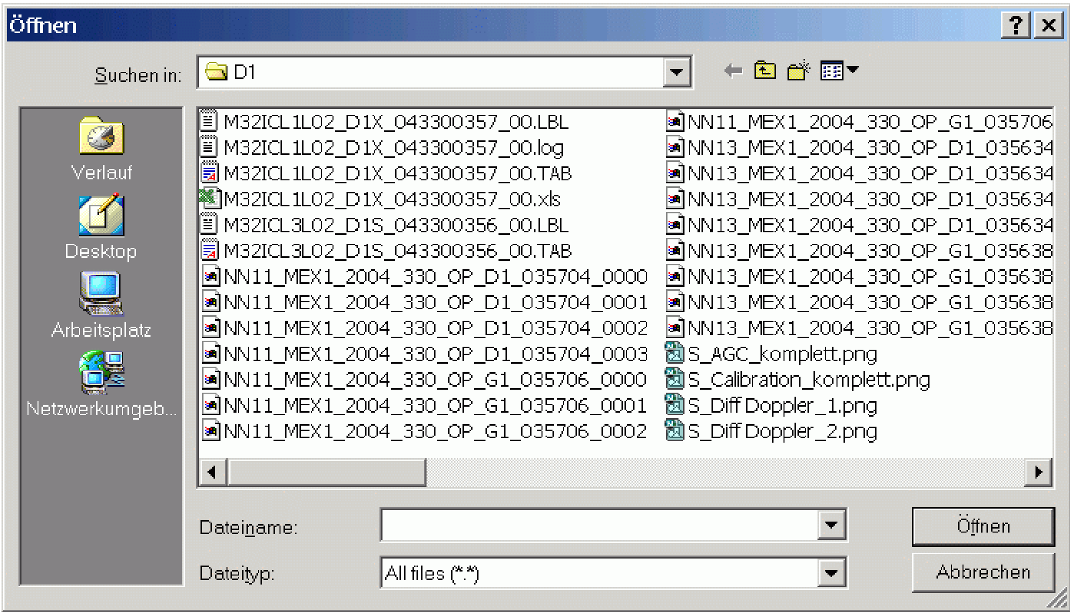


Figure 4-1: Graphical interface for selection of the input files.

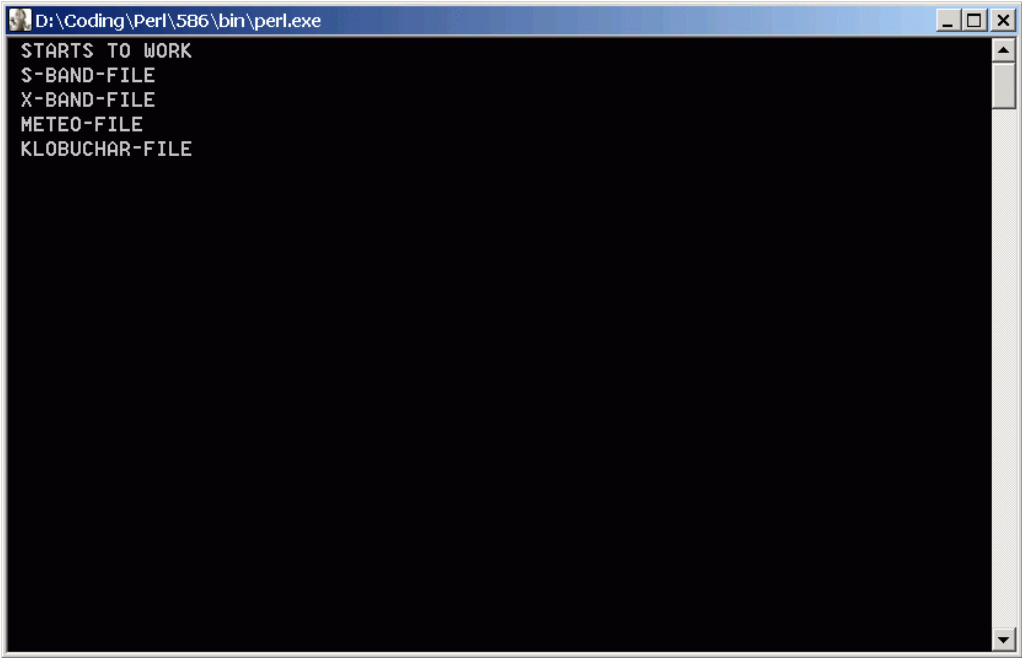


Figure 4-2: DOS window showing information about the kind of file needed to be inputted and processing status.

4.1 GRAPHICAL INTERFACE

The graphical interface shown in Figure 4-3 is divided in several adjustment parts for processing. The programming language for the graphical interface is Perl.

1. Mission

- **MEX**: Mars-Express
- **ROS**: Rosetta
- **VEX**: Venus-Express

2. Observation type

- **Commissioning**: Part of the mission where the retrieved data are only used for calibration aims.
- **Occultation**: Occultation measurements are performed
- **Target Gravity**: A specified target is chosen for gravity measurements
- **Global Gravity**: Global measurements are performed
- **Phobos**: Gravity measurements at the Mars moon Phobos are performed (only for Mars-Express applicable)

3. Procession mode:

- **Occultation**: Only tropospheric calibration (see section 2.4.1 is applied)
- **Gravity**: Tropospheric and plasma calibration is applied. The plasma calibration is done via the differential Doppler (see section 2.4.2 and 2.4.3 for more details). If the conditions for plasma calibration are not fulfilled no plasma correction will be applied.

4. Automatically processing

In this part the year and the day of year of the data to process must be entered. If the data are automatically processed all other information required for processing are read in from the corresponding log file that is stored in the same folder as the data to process. Therefore no other options are need to be adjusted. The format of the year must be yyyy for example 2004 and for the day of year ddd for example 009. To process only one day start day and stop day have to be the same.

5. Additional processing information

- **One way operation**: If the information in the header and the active table of the IFMS Doppler files of level 1a are wrong the operation mode can be set manually to one way by setting this button.
- **Additional file for frequency correction**: If the information in the header and active table of the IFMS Doppler files of level 1a for frequency reconstruction are in both files not correct it is possible to add another file containing the correct frequency reconstruction information to the process operation. This can be done by setting this button
- **Active table of X-Band is containing the correct frequency data**: If the information in the header and active table of the IFMS Doppler files of level 1a for frequency reconstruction are not equal the information in the X-Band data are used per default for both files. Does the S-band is containing the correct data and this data should be used this can be done by not setting this button.

6. Number of input files

This part defines the number of files to process and which kind of files are available. Both X-band and S-band files and the meteo file are required for processing. The processing can be done without a predict file and AGC file but not all columns of the output file will get a valid value. The Klobuchar file is only required for plasma correction (see section 2.4.4 for more details) for Occultation and for Gravity measurements if no differential Doppler is available.

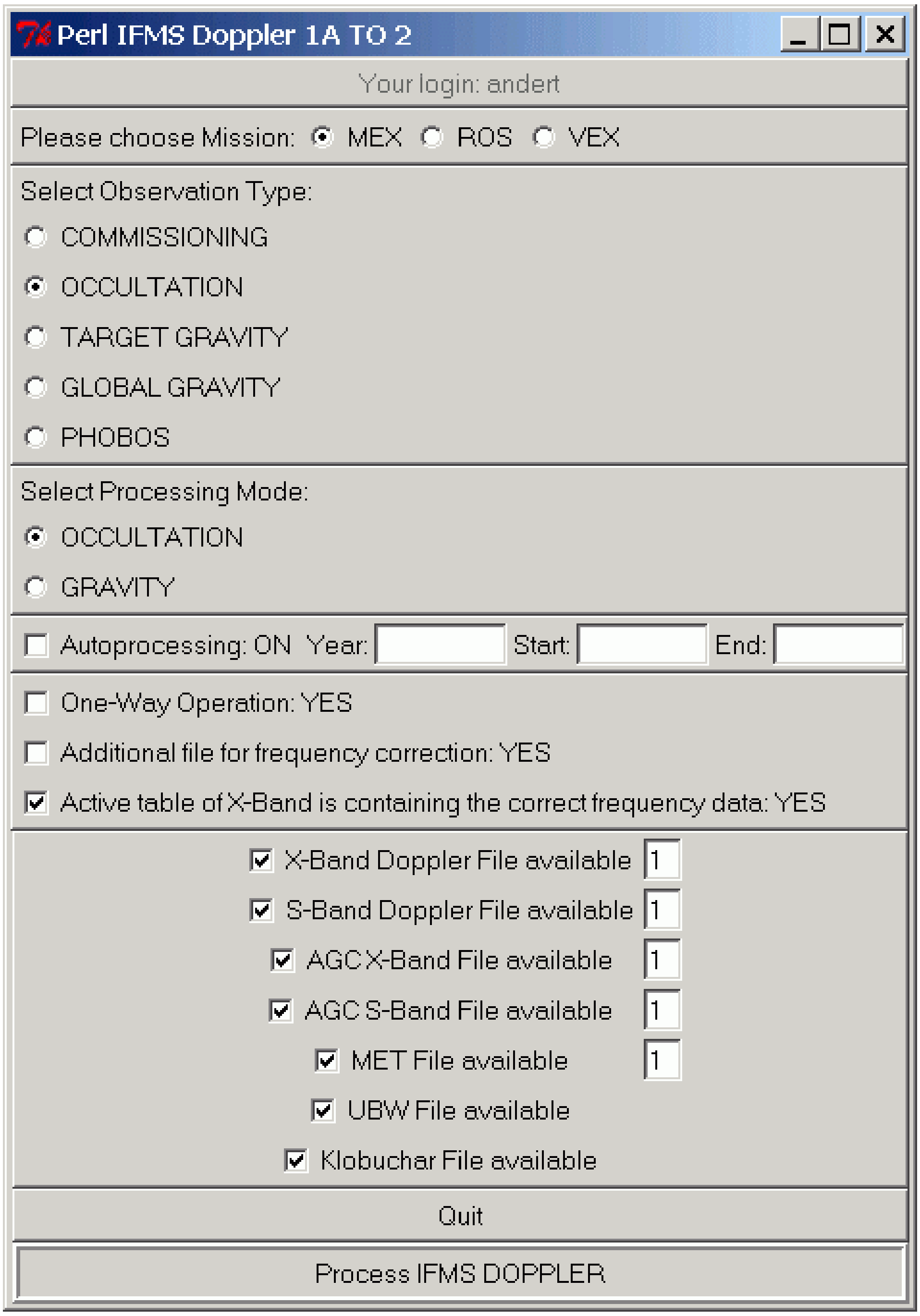


Figure 4-3: Graphical Interface for IFMS Doppler data processing

4.2 ADDITIONAL OUTPUT FILES

Several files with additional information about the processed data are produced during the processing operation by means of a PERL script which is called by the main script.

4.2.1 Data validation Excel sheet

An Excel sheet is automatically generated during the processing operation. The information contained in the Excel sheet is read in from the above described log file. This Excel sheet is used for data validation aims and is complemented with additional information during data validation and can accordingly be copied into a log book comprising processing information about all level 2 data.
The excel sheet will not be distributed and is only intended for internal use. Therefore the filename of the Excel sheet is not complying with [1]. But in order to relate the Excel sheet with the corresponding data files the Excel sheet gets the file name of the corresponding DOPPLER_OUTPUT_X_file but instead of the ending .tab the ending .xls is used.

4.2.2 Data illustration

During the processing operation a number of plots illustrating the processed data are automatically generated.

- **Correction of the earth atmosphere propagation** (column 11 in the data file of level 2) in Hz is plotted over the entire time period. This is done for S-band and X-band Doppler data.
- **Residual calibrated data** (column 12 in the data file of level 2) in Hz is plotted over the entire time period for S-band and X-Band Doppler data. In addition partial plots are generated. If the total number of sample points is bigger than 3600 the data to illustrate is divided into subintervals with 3600 data points or less for the remaining data points and plotted. If the total number of sample points is smaller than 3600 the data to illustrate is divided into subintervals with 600 data points or less for the remaining data points and plotted.
- **Received signal level** (column 13 in the data file of level 2) in dBm is plotted over the entire time period for S-band and X-Band Doppler data.
- **Differential Doppler** (column 14 in the data file of level 2) is plotted over the entire time period for S-band and X-Band Doppler data if it is available. In addition partial plots are generated. If the total number of sample points is bigger than 3600 the data to illustrate is divided into subintervals with 3600 data points or less for the remaining data points and plotted. If the total number of sample points is smaller than 3600 the data to illustrate is divided into subintervals with 600 data points or less for the remaining data points and plotted.

4.3 ERRORS

The following describes some errors that maybe occur during the processing operation.

- A kernel defined in the list of loaded kernels is not available in the folder where all kernels for processing are stored. Therefore the missing kernel has to be copied into the kernel folder. An example of the error message is shown in Figure 4-4.

```
D:\Coding\Perl\586\bin\perl.exe
Start:365 Ende:365

DOY_365_MEX
find_log done!!
 STARTS TO WORK

 ============================================================================

 Toolkit version: N0053

 SPICE(NOSUCHFILE) --

 The tenth file
 'Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\ORMM__041201000000_00105.BSP'
 specified by KERNELS_TO_LOAD in the file
 Z:\ddswork\process_data\Soft_Doppler_L2\Kernels\List_of_loaded_kernels.txt
 could not be located.

 A traceback follows.  The name of the highest level module is first.
 FURNSH --> ZZLDKER

 Oh, by the way:  The SPICELIB error handling actions are USER-TAILORABLE.  You
 can choose whether the Toolkit aborts or continues when errors occur, which
 error messages to output, and where to send the output.  Please read the ERROR
 "Required Reading" file, or see the routines ERRACT, ERRDEV, and ERRPRT.

 ============================================================================
Return code 1
Sorry, an error occurred! No output produced!
------------------------------------------------------------
```

Figure 4-4: Example of an error message if a kernel file is missing.

- A wrong kernel file containing ephemeris data with inappropriate time stamps is loaded. This has to be corrected in the module M_SPICE. An example of the error message is shown in Figure 4-5

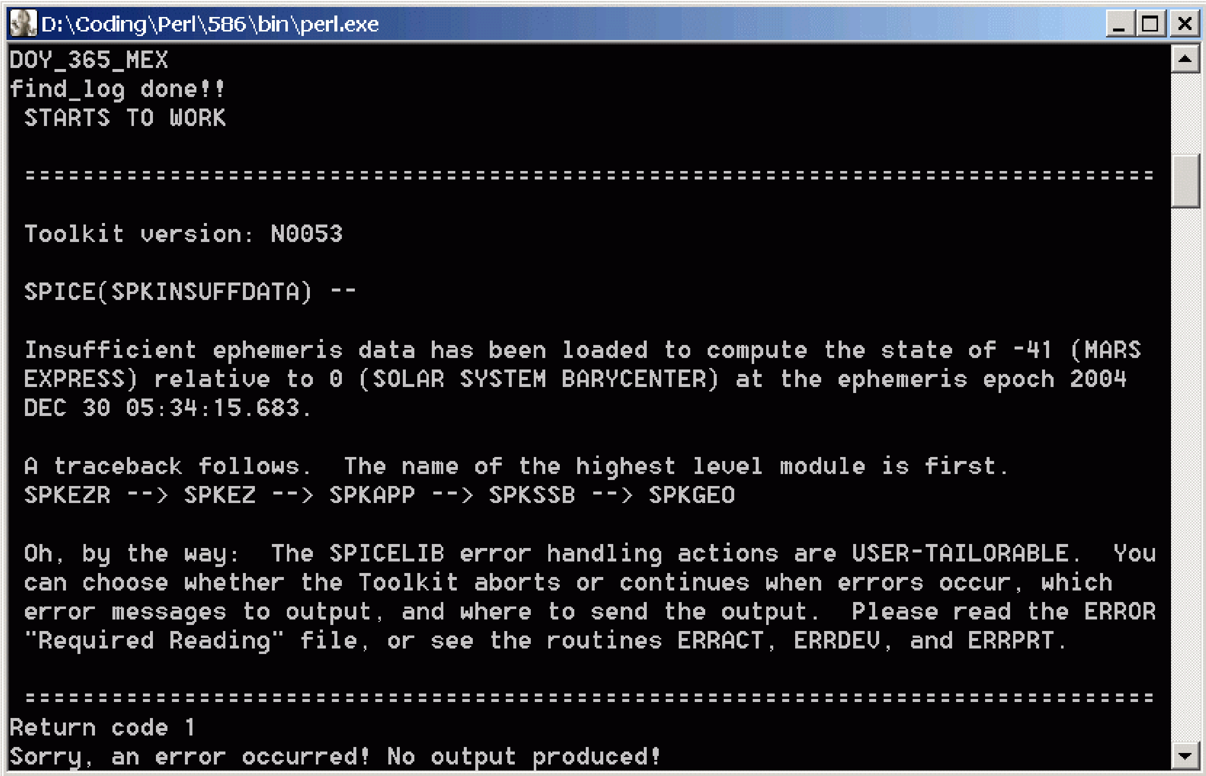


Figure 4-5: Example of an error message if a wrong kernel file is loaded.

- Two or more identical lines in the data file are existing and therefore the interpolation routine is not working. Consequently the redundant information has to be erased. This can happen in the meteo file of level 1a and the predict file. An example of the error message is shown in Figure 4-6. If the meteo file contains redundant data the terminal error arises after READ DOPPLER DONE.

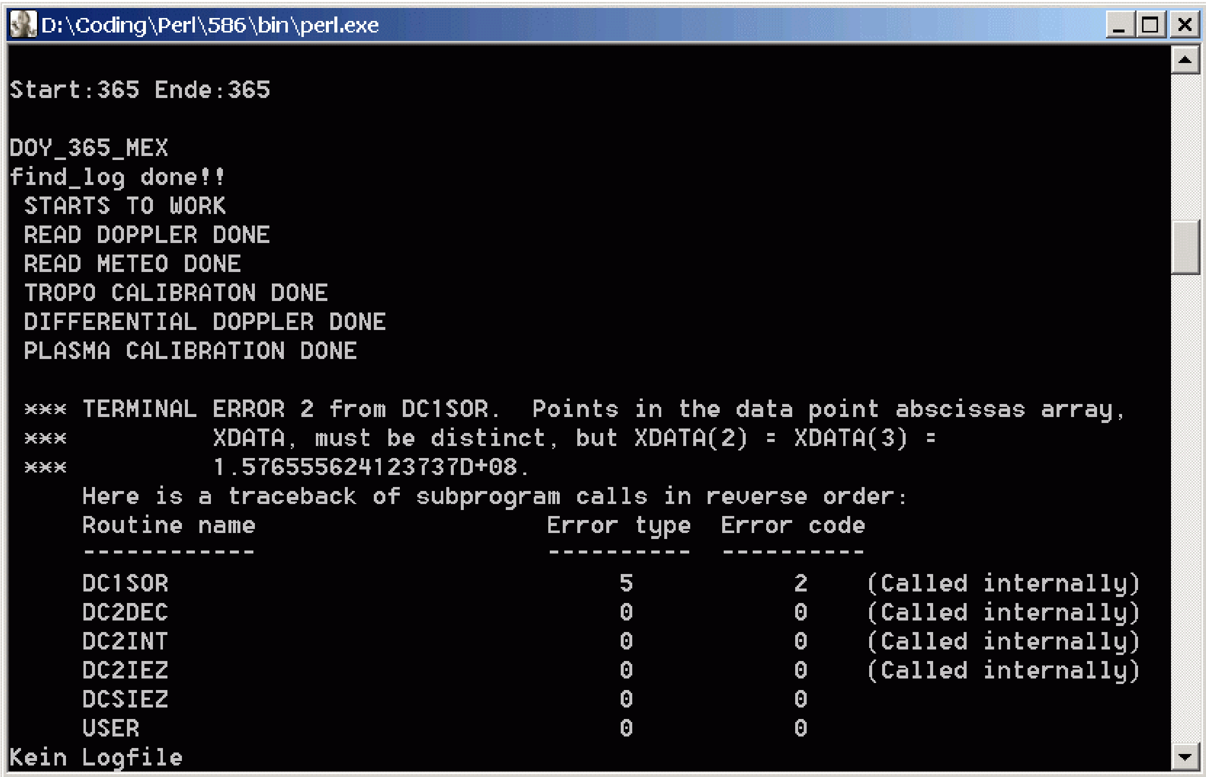


Figure 4-6: Example of an error message if redundant data is contained in the predict file.

APPENDIX A

Computation of the sky frequency received at ground station from doppler predicts

Acronyms:

fs_{gs} = frequency emitted from ground station
fs_{sc} = frequency emitted from spacecraft
fr_{sc} = frequency received at spacecraft
fr_{gs} = frequency received at ground station

Δf_{sc} = frequency shift received at spacecraft in the uplink signal emitted from groundstation
Δf_{gs} = frequency shift received at groundstation in the downlink signal emitted from the spacecraft
K = transponder conversion ratio

P_{UL} = doppler predict of the uplink signal independent from frequency
P_{DL} = doppler predict of the downlink signal independent from frequency

General relations:

$$P_{UL} = \frac{\Delta f_{sc}}{fs_{gs}}$$

$$P_{DL} = \frac{\Delta f_{gs}}{fs_{sc}}$$

<u>One-way case</u>

$$\Delta f_{gs} = fs_{sc} \cdot P_{DL}$$

it is needed

$$fr_{gs} = \Delta f_{gs} + fs_{sc}$$

therefore the sky frequency is

$$fr_{gs} = fs_{sc} \cdot P_{DL} + fs_{sc}$$

or

$$fr_{gs} = fs_{sc} \cdot \left(P_{DL} + 1\right)$$

Two-way case:

$$\Delta f_{sc} = fs_{gs} \cdot P_{UL}$$
$$\Delta f_{gs} = fs_{sc} \cdot P_{DL}$$

needed is

$$fr_{gs} = \Delta f_{gs} + fs_{sc}$$

therefore

$$fr_{gs} = fs_{sc} \cdot P_{DL} + fs_{sc}$$

or

$$fr_{gs} = fs_{sc} \cdot (P_{DL} + 1)$$

with

$$fs_{sc} = K \cdot fr_{sc}$$
$$\Rightarrow \quad fr_{gs} = K \cdot fr_{sc} \cdot (P_{DL} + 1)$$
$$\Rightarrow \quad fr_{gs} = K \cdot \left(fs_{gs} + \Delta f_{sc} \right) \cdot (P_{DL} + 1)$$
$$\Rightarrow \quad fr_{gs} = K \cdot fs_{gs} \left(1 + \frac{\Delta f_{sc}}{fs_{gs}} \right) \cdot (P_{DL} + 1)$$
$$\Rightarrow \quad fr_{gs} = K \cdot fs_{gs} (1 + P_{UL}) \cdot (1 + P_{DL})$$

and therefore the sky frequency is

$$fr_{gs} = K \cdot fs_{gs} (1 + P_{UL} + P_{DL} + P_{UL} \cdot P_{DL})$$

APPENDIX B

Computation of the plasma correction using the differential doppler

The differential doppler is computed via

$$df = f_{S,antenna}\Big|_{tropo\_corrected} - \frac{3}{11} f_{X,antenna}\Big|_{tropo\_corrected} \tag{1.12}$$

or

$$df = -\frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\} f_S \frac{dI}{dt} \tag{1.13}$$

therefore the temporal change in electron content is

$$\frac{dI}{dt} = -\left\{\frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\right\}^{-1}\frac{df}{f_S}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\}^{-1} \tag{1.14}$$

the plasma correction for S-Band is

$$f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} + \frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\frac{1}{f_S}\frac{dI}{dt} \tag{1.15}$$

and for X-Band

$$f_{X,antenna,cal} = f_{X,antenna}\Big|_{tropo\_corrected} + \frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\frac{1}{f_X}\frac{dI}{dt} \tag{1.16}$$

If equation (1.14) is inserted into (1.15)

$$f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} + \cancel{\frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}}\frac{1}{f_S}\left(-\cancel{\left\{\frac{1}{2c}\frac{1}{4p^2}\frac{e^2}{m_e e_0}\right\}^{-1}}\frac{df}{f_S}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\}^{-1}\right)$$

$$\Rightarrow \quad f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} - df\left\{\frac{f_S^2}{f_S^2} - \frac{f_S^2}{f_X^2}\right\}^{-1}$$

and with the general relations

$$f_X = \frac{11}{3} f_S \quad \Leftrightarrow \quad \frac{f_X}{f_S} = \frac{11}{3} \quad \Leftrightarrow \quad \frac{f_S}{f_X} = \frac{3}{11} \tag{1.17}$$

follows than

$$f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} - df \left\{1 - \frac{9}{121}\right\}^{-1}.$$

Therefore equation (1.15) ca be written as

$$\boxed{f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} - df\,\frac{121}{112}} \tag{1.18}$$

A similar computation can be done for equation (1.16).

$$\Rightarrow \quad f_{X,antenna,cal} = f_{X,antenna}\Big|_{tropo\_corrected} - df \left\{\frac{f_X f_S}{f_S^2} - \frac{f_X f_S}{f_X^2}\right\}^{-1}$$

Using equation (1.17)

$$\Rightarrow \quad f_{X,antenna,cal} = f_{X,antenna}\Big|_{tropo\_corrected} - df \left\{\frac{11}{3} - \frac{3}{11}\right\}^{-1},$$

therefore equation (1.16) can be written as

$$\boxed{f_{X,antenna,cal} = f_{X,antenna}\Big|_{tropo\_corrected} - df\,\frac{33}{112}} \tag{1.19}$$

APPENDIX C

Earth Klobuchar Ionosphere Model (see attached document CGIM_ANNEX_C.pdf)

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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).

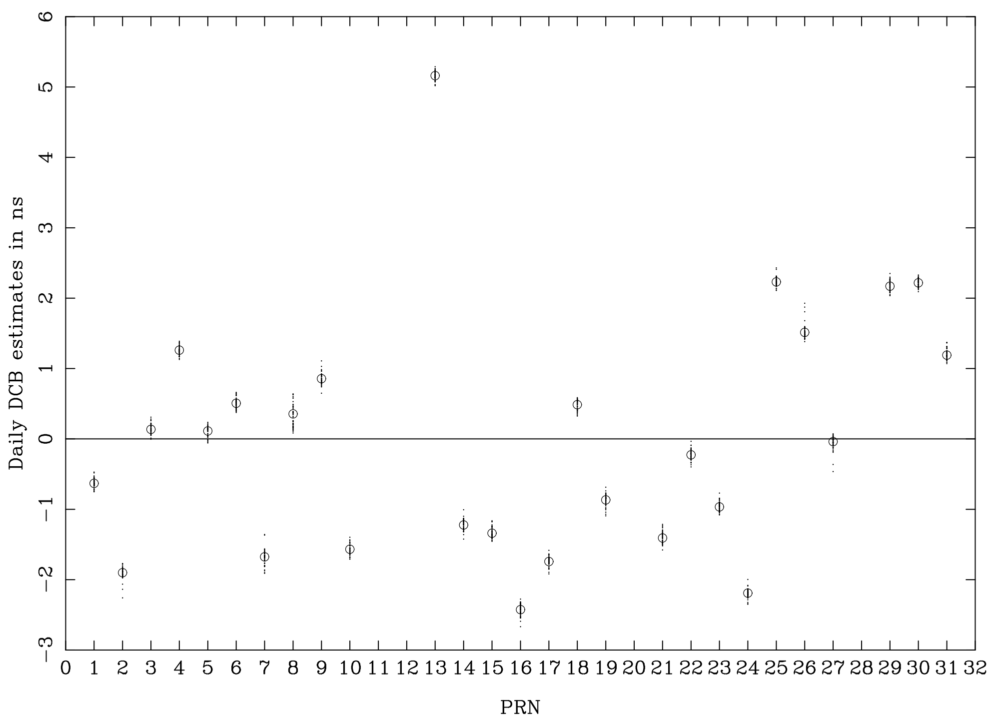


Figure 1. Daily PRN-specific DCB estimates (dots) for 27 GPS satellites from day 022, 1998, to day 071, 1998, and combined DCBs (circles)

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.

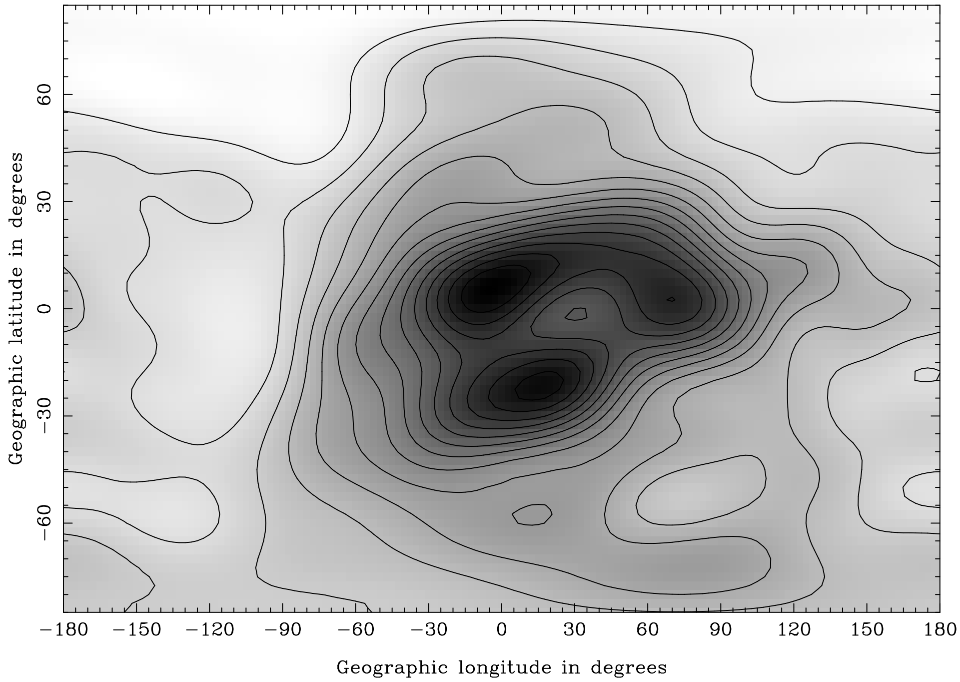
Table 1. Combined DCBs and weighted RMS errors of daily estimation

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			

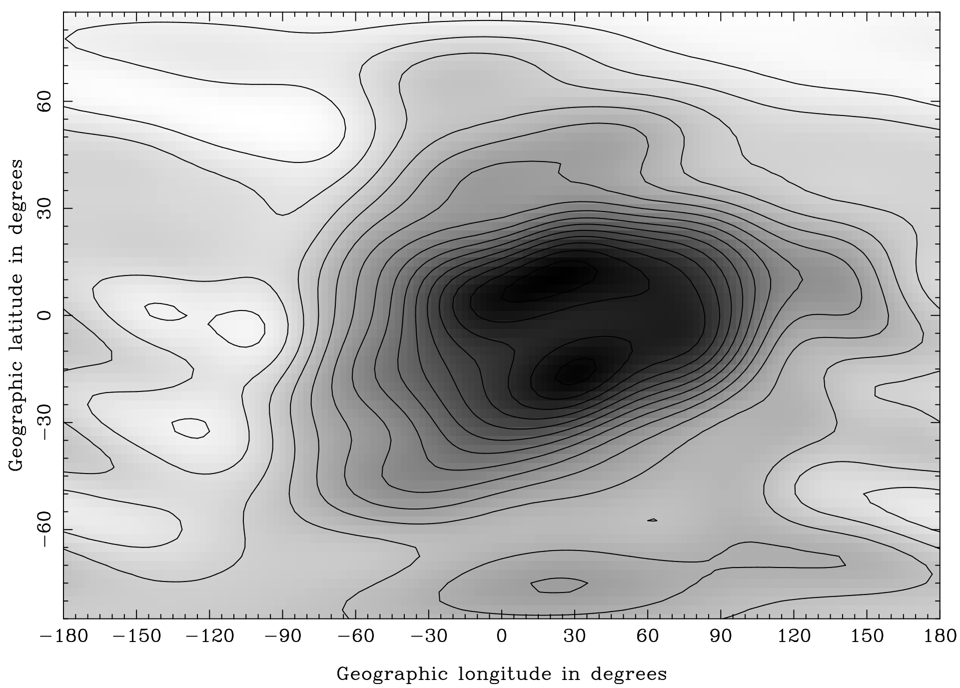
Figure 2 shows snapshots of (a) a *phase*-derived and (b) a *code*-derived 24-hour TEC map for day 017, 1998 (taken at 12:00 UT). The number of contributing stations was 79 on that particular day. Light fields indicate small TEC, dark ones large TEC (up to 37.6 and 39.0 TECU here). The level lines are 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

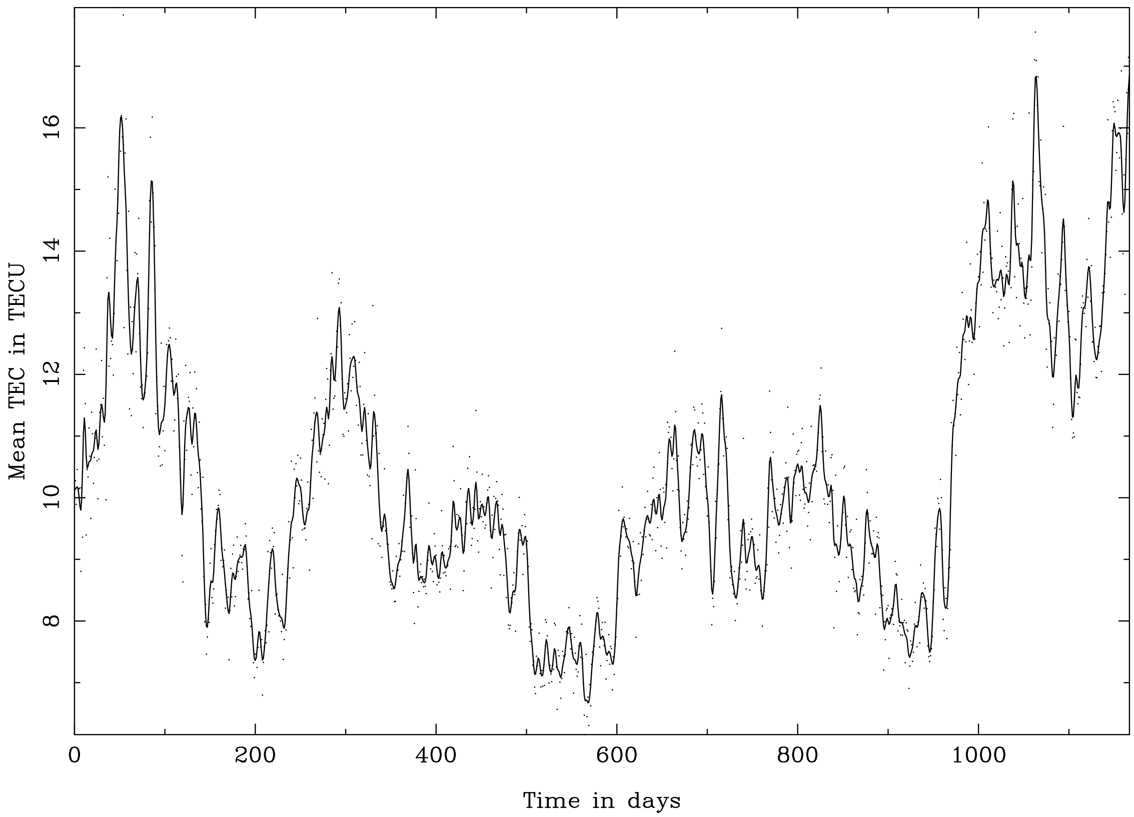
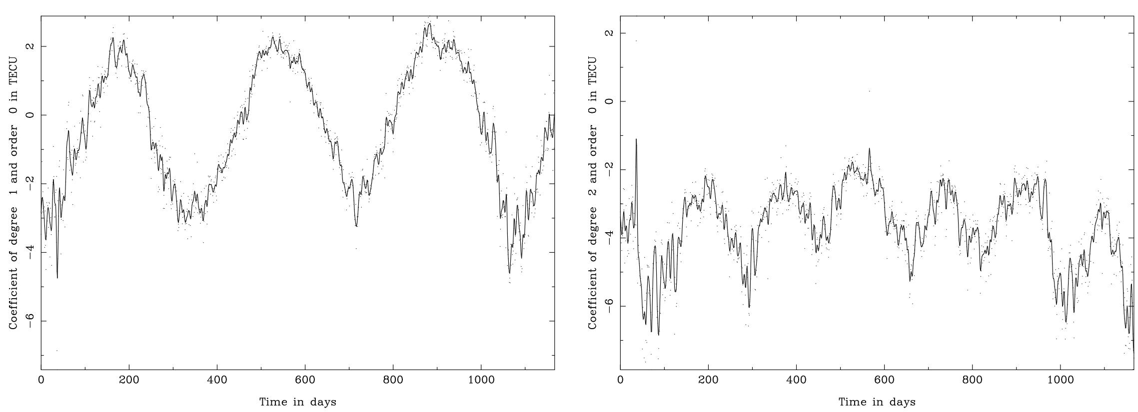


Figure 3. Zero-degree coefficient (mean TEC) from day 001, 1995 to day 072, 1998

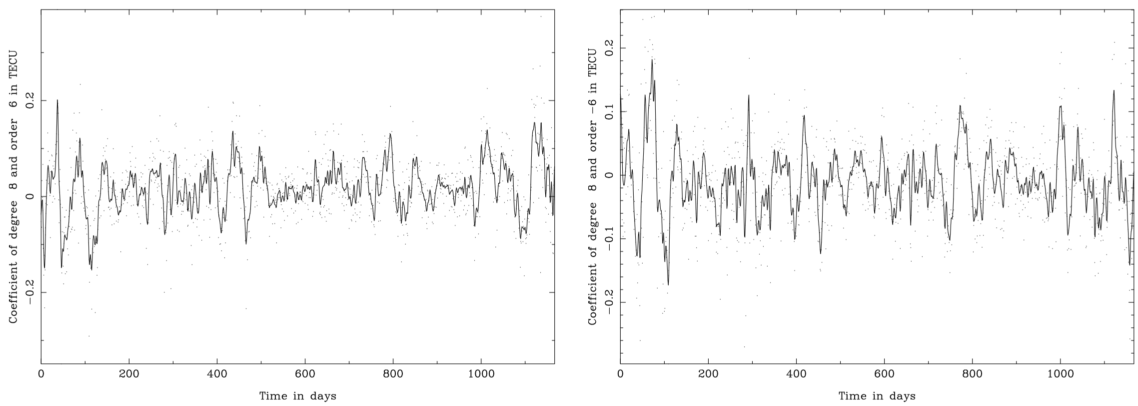
Figures 4 and 5 illustrate a few other SH coefficients showing similar periodicities and features as mentioned above.



(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)

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

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

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

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:

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

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

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

$h\,\Delta t$ 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.

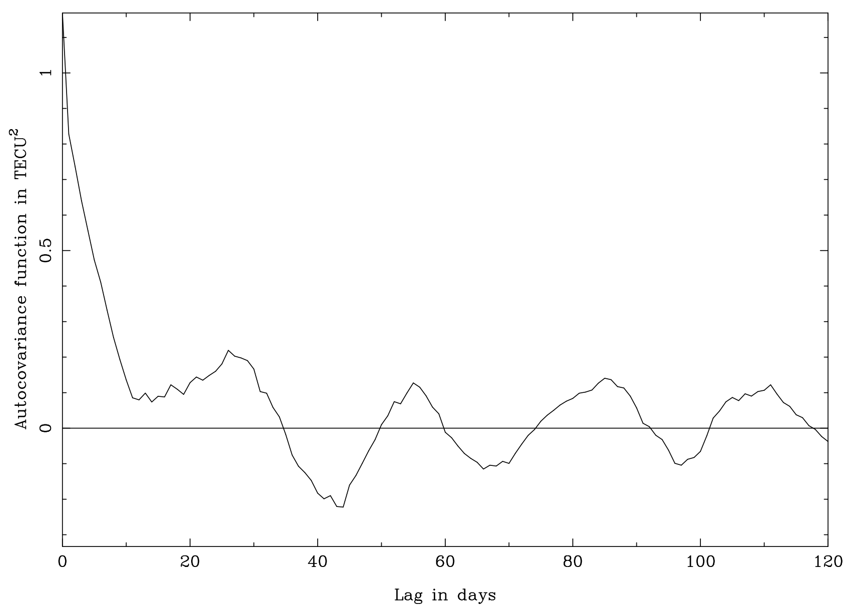
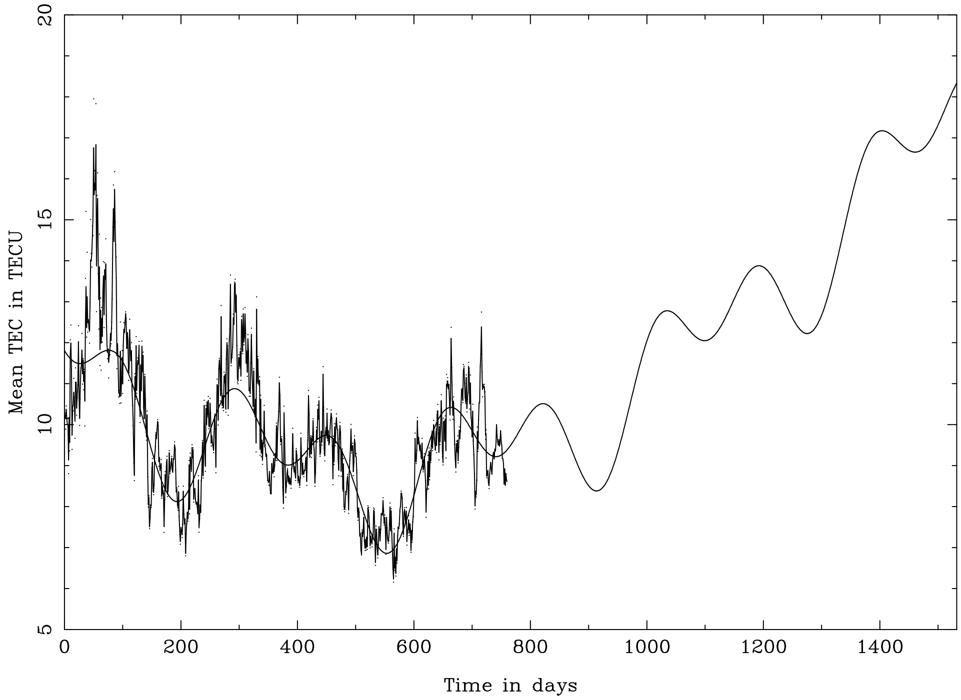
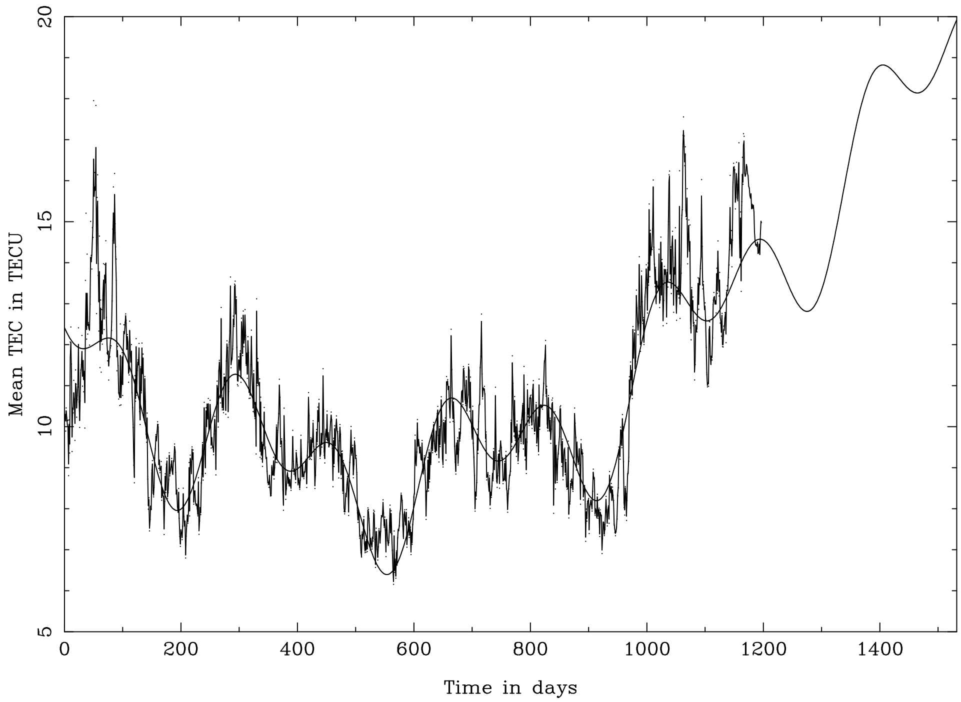


Figure 6. Autocovariance function of zero-degree coefficient for lags up to 120 days

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.

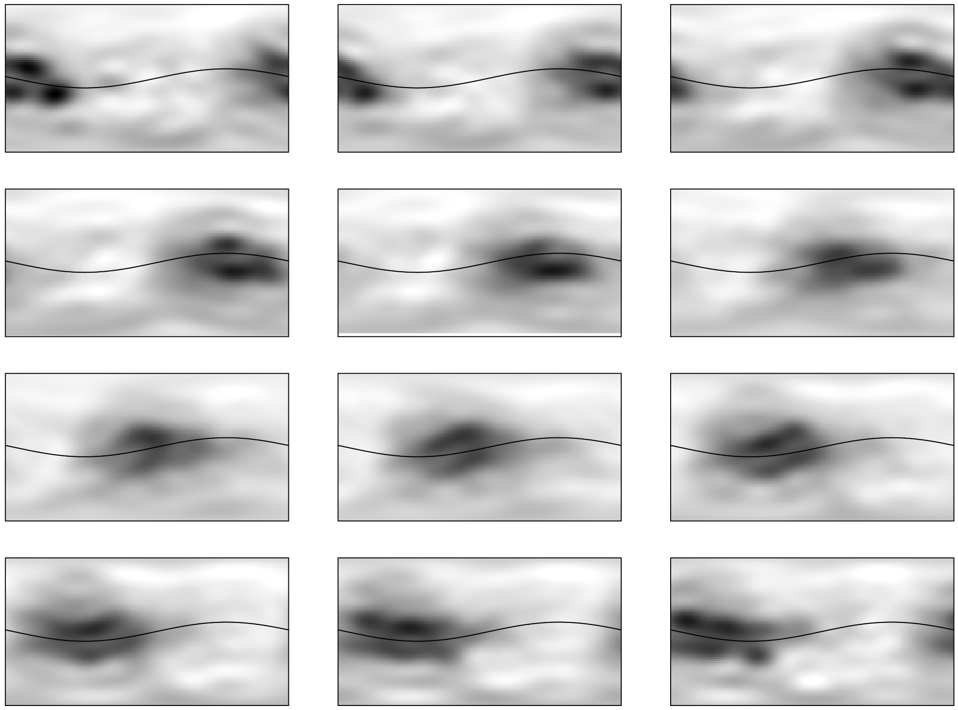
SH expansions are well suited to model time-independent quantities given on a spherical surface. When dealing with the ionosphere, the entire sphere is probed by GPS stations when deriving one-day TEC maps. The disadvantage is a poor temporal resolution because of the assumption of a "frozen" ionosphere 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

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

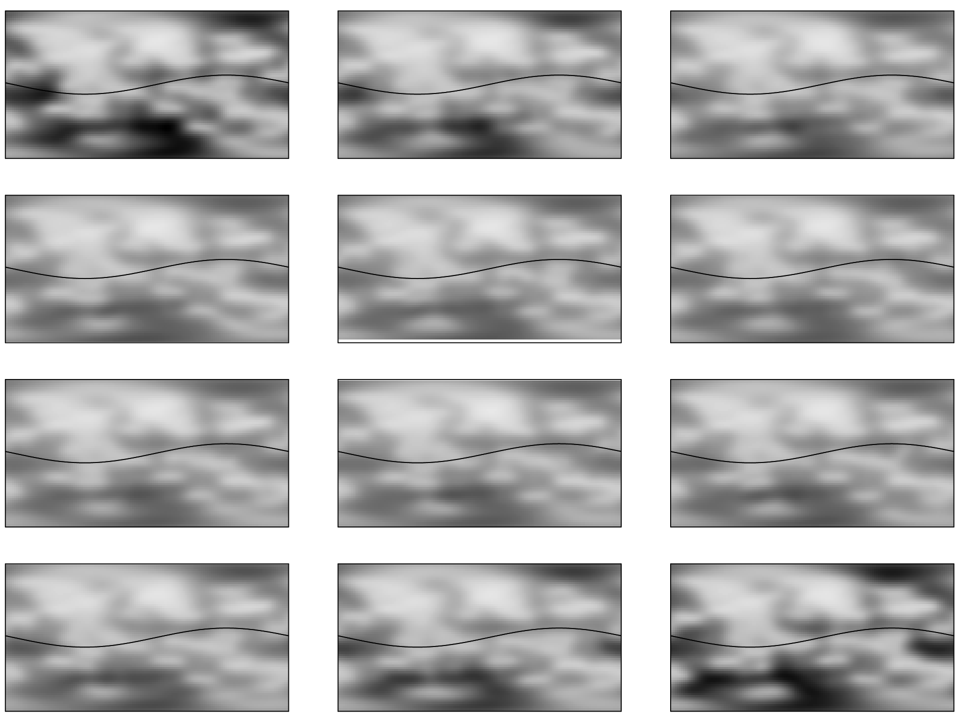
to the system of normal equations stemming from actual observations. Note that the a priori sigmas $\sigma_{\Delta e_{ij}}$ used for the pseudo-observations Δe_{ij} do not affect the "absolute" TEC determinations. Optimal values for these sigmas have to be found experimentally. Due to the fact that we 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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APPENDIX D

Klobuchar File Format Description (see attached document CGIM_ANNEX_D.pdf)

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

- 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 $T_i \le t < T_{i+1}$ 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.

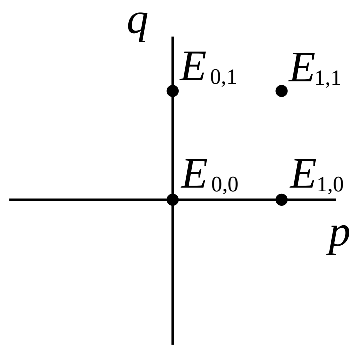

Figure 1: Bivariate interpolation using the nearest 4 TEC values $E_{i,j}$

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:

`ccceddddh.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.

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Appendix A: IONEX Version 1 Format Definitions and Examples

Table 1: Ionosphere map file — header section description

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

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

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

(Records marked with "*" are optional)

Table 2: Ionosphere map file — data record description

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

(Records marked with "*" are optional)

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

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

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

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

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

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

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

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

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

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

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

Appendix B: Auxiliary Data Blocks

GPS/GLONASS-Related Data Block

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

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

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

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

and

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

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

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

Table 1: Differential code biases — format definitions

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

(Records marked with "*" are optional)

Table 2: Differential code biases — example

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

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

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