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IFMS/TTCP 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
ESTRACK	ESA TRACKing stations
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
TTCP	Telemetry, Tracking and Command Processor
TWOD	Two-way dual-frequency mode
TWOS	Two-way single-frequency mode
USO	Ultra Stable Oszillator
X-TX	X-band Transmitter

Contents

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1 INTRODUCTION

1.1 SCOPE

This document specifies the requirements for the development of the IFMS/TTCP processing software, transferring Level 1a IFMS/TTCP data towards Level 2. The software shall analyze radio Doppler tracking data recorded at the IFMS/TTCP receiving systems of the ESA ESTRACK ground stations. AGC and meteo data are handeled via the IFMS/TTCP software.

1.2 REFERENCED DOCUMENTS

	Reference Number	Title	Issue Number	Date
[1]	MEX-MRS-IGM-IS-3016 ROS-RSI-IGM-IS-3087 VEX-VRA-IGM-IS-3009	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 ROS-RSI-IGM-DS-3121 VEX-VRA-IGM-DS-30??	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
[5]	TTCP-ICD-SOFT_1.3.pdf	TTCP-to OCC document	1.3	

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

In 2018, the IFMS units in the ESA ESTRACK ground stations were replaced by TTCP units. The processed file type afterwards changes from IFMS to TTCP. New specifications are only given when the TTCP processing differs from the IFMS processing.
The MAIN program shall read the IFMS/TTCP level 1a Doppler data both at S-band and X-band and computes the observed frequency received at the groundstation from the data contained therein. 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 a log file containing processing information shall be produced via M_OUTPUT. The according label files shall be generated via M_LABEL.

2.1.1 Modules

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/TTCP level 1a Doppler X-band S-band	 IFMS_DOPPLER_X IFMS_DOPPLER_S
predicted Doppler file	PREDICT_FILE
IFMS/TTCP_Meteo file level 1a	IFMS_METEO
IFMS/TTCP 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

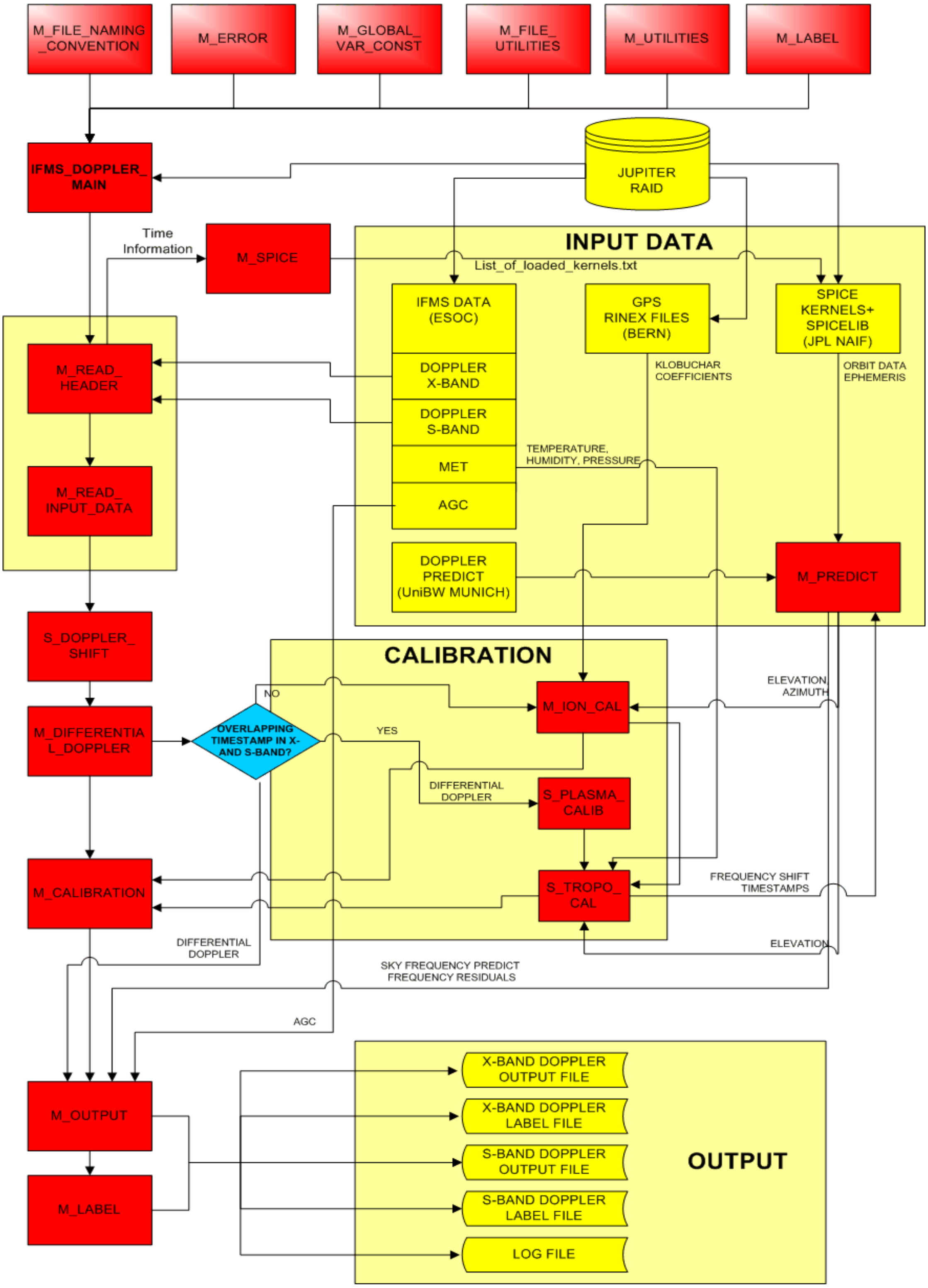
Actual transmitted frequencies (up and downlink) may vary according to expected Doppler shift (approx. 10 – 100 kHz).

IFMS-DEF-1031: Transponder constants and ratios k

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 the evaluation software for the IFMS Doppler data (TTCP processing similar)

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/TTCP 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/TTCP level 1a Doppler data file 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/TTCP 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]/[5] 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/TTCP level 1a Doppler data at X-band and S-band and reconstructs the observed antenna frequency as follows using therein contained data. The required information contained in the IFMS/TTCP level 1a Doppler data at X-band and S-band for this computation are listed in detail in IFMS-DEF-2402 and TTCP-DEF-2402. It is important to know that the timestamp in the original IFMS/TTCP level 1a Doppler data is not the same as for the observed antenna frequency (see IFMS-SPEC-2401**:** The antenna frequency is computed between two time stamps ti and ti+1 of the original IFMS level 1a Doppler data. Therefore the timestamp tantenna of the antenna frequency fantenna is computed via:

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

and TTCP-SPEC-2401).

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

$$f_{up} = f_{offset,up} + f_{inter} + f_{LO}$$

$$f_{down} = k \cdot f_{up}$$

$$\Delta count(t_i) = count(t_i) - count(t_{i-1})$$

$$\Delta time = \frac{\Delta count}{17.5 \cdot 10^6}$$

$$\Delta phase(t_i) = phase(t_i) - phase(t_{i-1})$$

$$\Delta phase_{Dop=0} = \Delta time \cdot (f_{down} - f_{Dconv} - 70MHz)$$

$$\Delta phase_{Dop}(t_i) = \Delta phase(t_i) - \Delta phase_{Dop=0}$$

$$f_{antenna}(t_i) = k \cdot f_{up} + \frac{\Delta phase_{Dop}(t_i)}{\Delta time\,(t_i)}$$

For detailed information see [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
ActualCarrierFreqOffset	$f_{offset,up}$	Expected upl. Doppler shift **Contained in ActiveTable**	Hz
UlmCarFrSel	f_{inter}	Intermediate frequency after downconversion Ca. 70 MHz or 230 MHz **Contained in ActiveTable**	Hz
FreqUplkConv	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
DownlinkCarrierFreq	f_{down}	Spacecraft downlink carrier frequency	Hz
FreqDnlkConv	f_{Dconv}	Downlink carrier conversion (before IFMS output) for the signal received by the IFMS.	Hz
Count	$count(t_i)$	count at given timestamp t_i	
DeltaCount	$\Delta count(t_i)$	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	$\Delta time$	Time interval between two timestamps t_i and t_{i-1}	sec
Phase	$phase(t_i)$	measured phase in cycles	cycles
DeltaPhase	$\Delta phase$	Variation in phase between two timestamps t_i and t_{i-1} ,	cycles
ZeroDopplerDeltaPhase	$\Delta phase_{Dop=0}$	Phase change in $\Delta time$ assuming that Doppler shift is zero	cycles
DeltaPhaseDoppler	$\Delta phase_{Dop}$	Phase change in $\Delta time$ for the true Doppler shift	cycles

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

$$f_{up} = f_{TX} + f_{UC}$$

$$f_{down} = k \cdot f_{up}$$

$$\Delta count(t_i) = count(t_i) - count(t_{i-1})$$

$$\Delta time = \frac{\Delta count}{17.5 \cdot 10^6}$$

$$\Delta phase(t_i) = phase(t_i) - phase(t_{i-1})$$

$$\Delta phase_{Dop=0} = \Delta time \cdot (f_{Dconv} - f_{down} - f_{base})$$

$$\Delta phase_{Dop}(t_i) = \Delta phase(t_i) - \Delta phase_{Dop=0}$$

$$f_{antenna}(t_i) = k \cdot f_{up} + \frac{\Delta phase_{Dop}(t_i)}{\Delta time\,(t_i)}$$

For detailed information see [5] section 8.4.

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

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

TTCP-DEF-2402: Definitions:

Acronyms as specified in [5]	**Symbol**	**Explanation**	**SI units**
StFreqTxFreq	F_{TX}	Carrier base frequency appr. 230 MHz **Contained in ActiveTable**	Hz
StFreqTxUpConv	F_{UC}	Uplink conversion parameter **Contained in ActiveTable**	Hz
UplinkCarrierFreq	f_{up}	Uplink carrier frequency	Hz
DownlinkCarrierFreq	f_{down}	Spacecraft downlink carrier frequency	Hz
StFreqRxDnConv	f_{Dconv}	Downlink conversion parameter **Contained in ActiveTable**	Hz
integ_phase_ref_freq	f_{base}	Reference frequency which is the nearest integer MHz value of f_{Dconv}-f_{down} **Contained in the Header**	Hz
Count	count($_{ti}$)	count at 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
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

IFMS-SPEC-2403: The uplink frequency f_{up} (result from IFMS-SPEC-2401/TTCP-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/TTCP-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/TTCP 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.):

$$\Delta_{dry}(E) = \frac{10^{-6}}{5} \frac{77.64 \frac{p}{T}}{\sin\left(\sqrt{E^2 + 6.25}\right)} \left[40136 + 148.72(T - 273.16)\right]$$
$$\Delta_{wet}(E) = \frac{10^{-6}}{5} \frac{-12.96T + 3.718 \cdot 10^5}{\sin\left(\sqrt{E^2 + 2.25}\right)} \frac{e}{T^2} 11000 \tag{1.1}$$

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:

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

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

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

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

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

for the one-way radio link.

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

$$m_{ONE} = \tau_{tropo} \cdot f_{down} \tag{1.4}$$

and for the two-way radio link:

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

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

$$\Delta f_{ONE,tropo} = \frac{dm_{ONE}}{dt} \tag{1.6}$$

and for the two-way radio link:

$$\Delta f_{TWO,tropo} = \frac{dm_{TWO}}{dt} \tag{1.7}$$

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 Differential Doppler

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: Differential Doppler
The result from IFMS-SPEC-2363 is taken to compute the differential Doppler

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

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

2.4.3 Plasma calibration using the differential doppler

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: Plasma calibration
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.

$$\begin{aligned} \delta f &= -\frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\left\{\frac{1}{f_S^2}-\frac{1}{f_X^2}\right\} f_S \frac{dI}{dt} \\ \Rightarrow \frac{dI}{dt} &= -\left\{\frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\right\}^{-1}\frac{\delta f}{f_S}\left\{\frac{1}{f_S^2}-\frac{1}{f_X^2}\right\}^{-1} \end{aligned} \tag{1.9}$$

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

$$\Delta f_{S,plasma,cal} = \frac{40.31}{c}\frac{1}{f_S}\frac{dI}{dt}$$
$$\Delta f_{X,plasma,cal} = \frac{40.31}{c}\frac{1}{f_X}\frac{dI}{dt} \quad (1.10)$$

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

$$\Delta f_{S,plasma,cal} = \delta f\,\frac{121}{112}$$
$$\Delta f_{X,plasma,cal} = \delta f\,\frac{33}{112} \quad (1.11)$$

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.

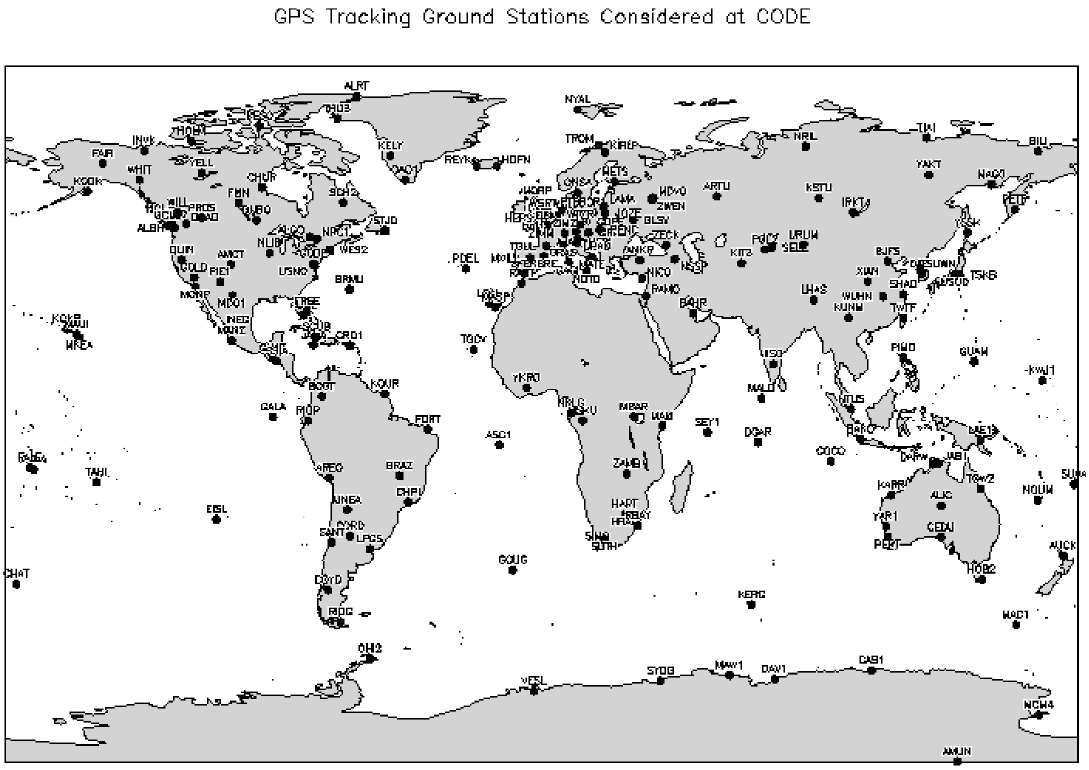


Figure 2-2: GPS Tracking Ground Stations

CODE computes Klobuchar-style ionospheric coefficients (alphas and betas) best fitting the IONosphere map EXchange data (IONEX) on a regular basis.
The 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 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 τ_{iono} depends on the local time at the ground station side. For the calculation of τ_{iono} the following parameters are used:

1. **Local Time t:**

   t = 4.32·long_i + TOW

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

   a = azimuth·pi /180
   !
3. **Elevation angle e (in semicircles):**

   e = elev·1./180
   !
4. **Earth Centered angle psi:**

   psi = 0.0137/ (e+0.11) - 0.022

5. **Subionospheric longitude long_i :**

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

6. **Subionospheric latitude lat_i :**

   lat_i = phi·1./180+ psi·DCOS(a)

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

   t = DMOD(t,86400.) !

8. **Slant factor sf:**

   sf = 1. + 16. · $(0.53\text{-}e)^3$!

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 τ_{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

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

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

$$\Delta f_{iono} = \frac{dm}{d\tau_{iono}}$$

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 tropospheric 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 $\Delta f_{pred,calib}$ 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/TTCP 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

rggtttxL02_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 32 = ESA New Norcia xx = ESA Cebreros XX = ESA Malargue	32
tttx	Data source IFMS closed-loop ttt = ICL x = 1 => NN11 x = 2 => NN12 x = 3 => NN13 Data source TTCP closed-loop ttt=TCL x = 1 => NN11 x = 2 => NN12	ICL1 TCL1
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/TTCP 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/TTCP 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 (see Appendix C).*	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 to one milliwatt (dBm).* <u>*Open-loop (RSR):*</u> *Signal level in decibels (dB) relative to an arbitrary reference.*	dBm / dB	0.1 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 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 (see Appendix C).*	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	Hz	10^{-6} Hz

	column 9 minus 10		
13	Received S-band signal level *Closed-loop data:* *Signal level from AGC in decibels relative to one milliwatt (dBm).* *Open-loop (RSR):* *Signal level in decibels (dB) relative to an arbitrary reference.*	dBm / dB	0.1 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/TTCP 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/TTCP 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/TTCP level 1a Doppler data file are used per default from the IFMS/TTCP 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 TTCP 1 or 2	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.

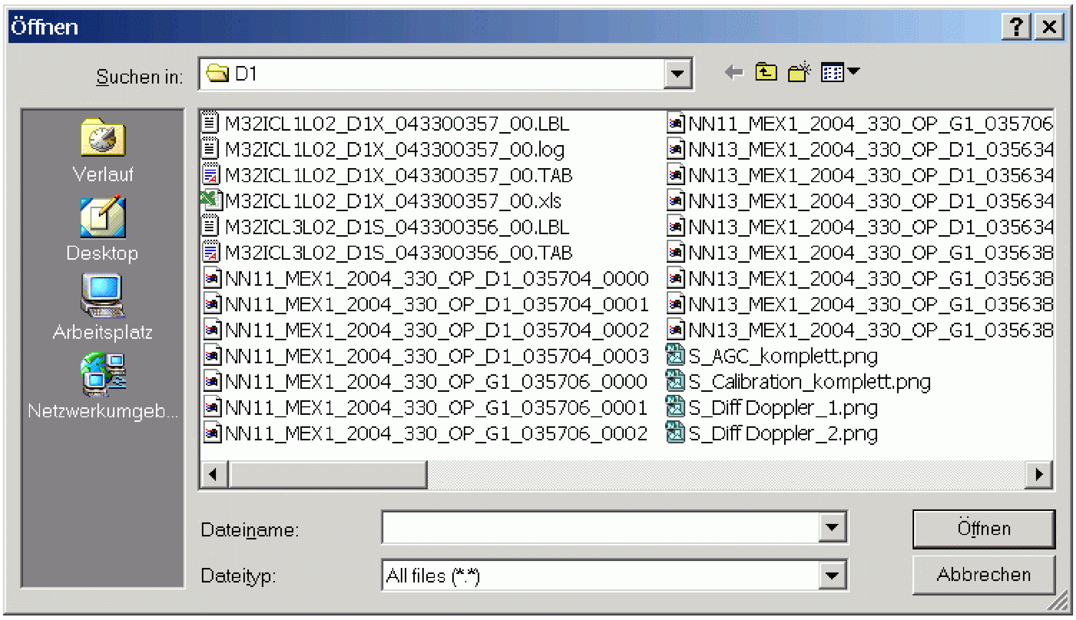


Figure 4-1: Graphical interface for selection of the input files.

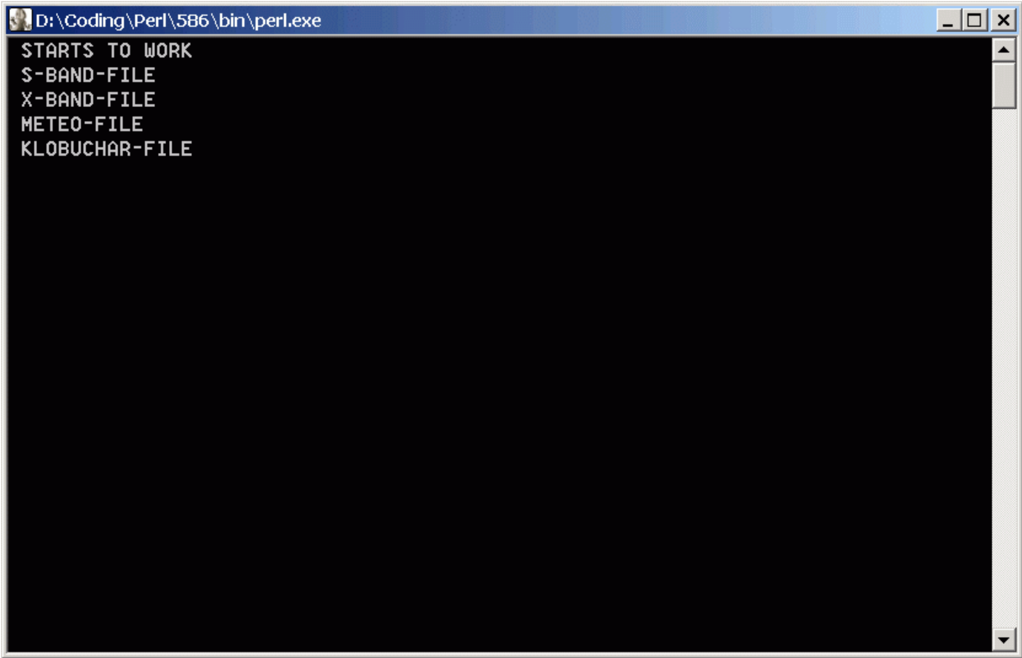


Figure 4-2: DOS window showing information about the kind of file needed to be inputted and processing status.

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/TTCP 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/TTCP 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.

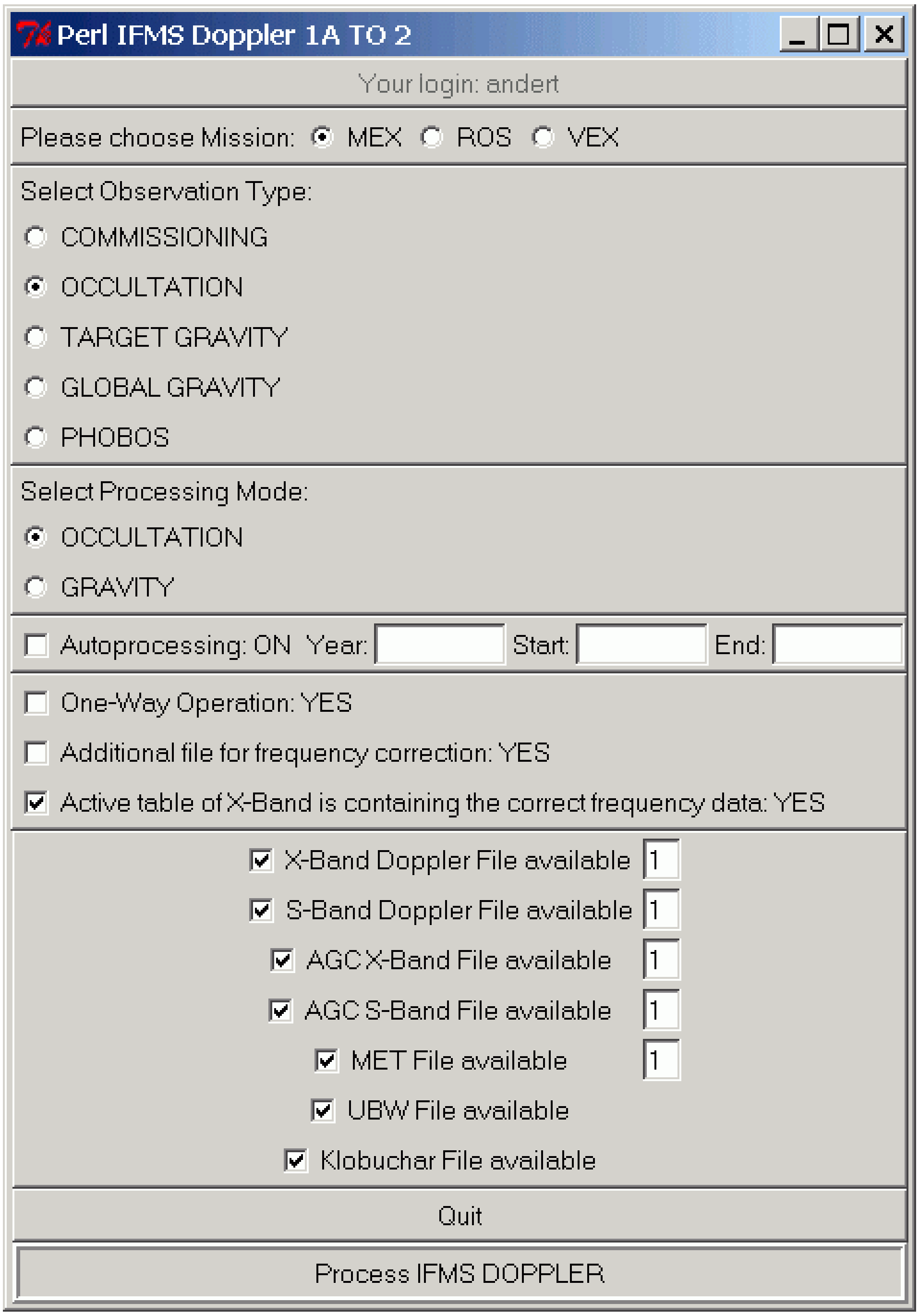


Figure 4-3: Graphical Interface for IFMS/TTCP Doppler data processing

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.

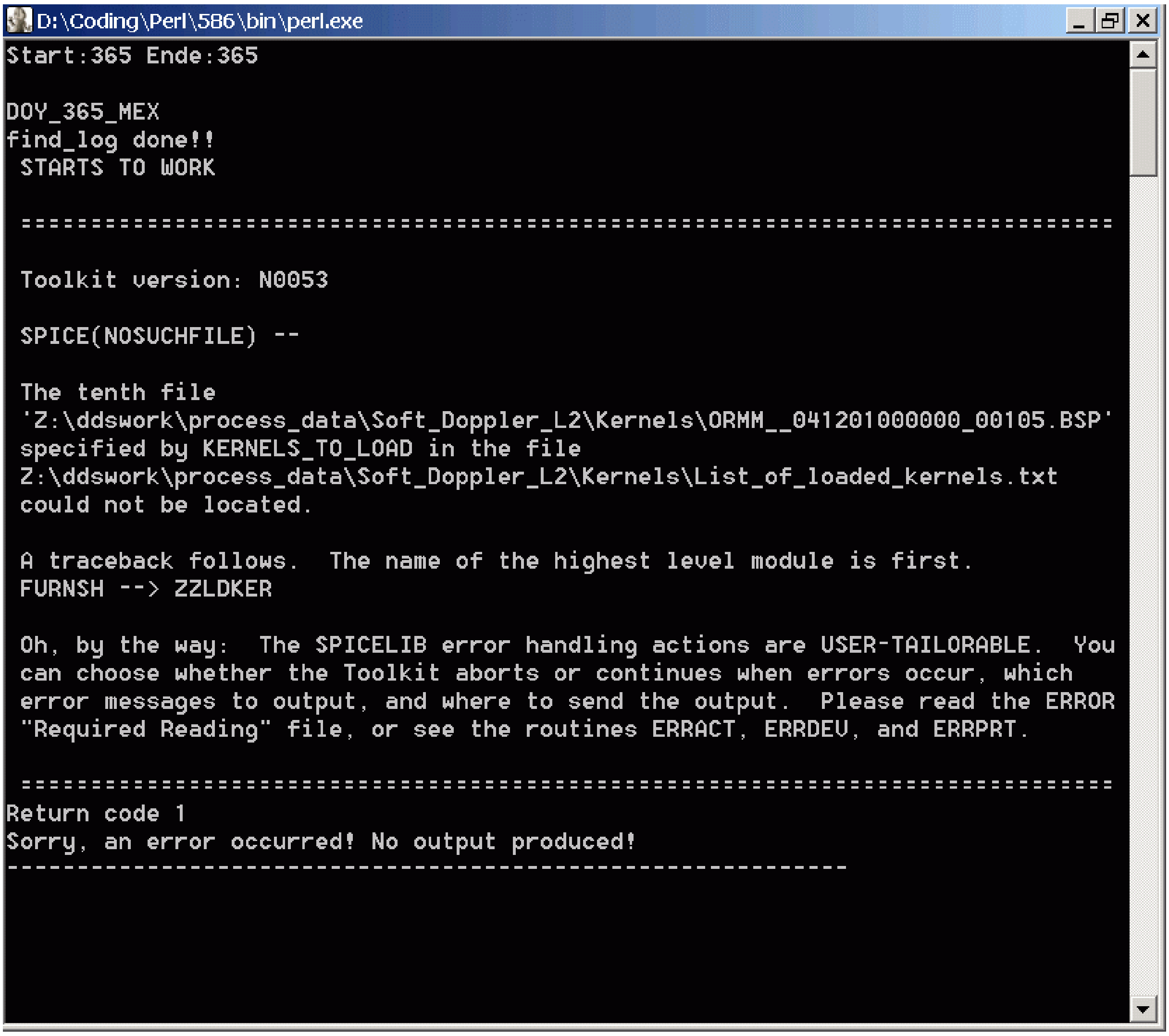


Figure 4-4: Example of an error message if a kernel file is missing.

- 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

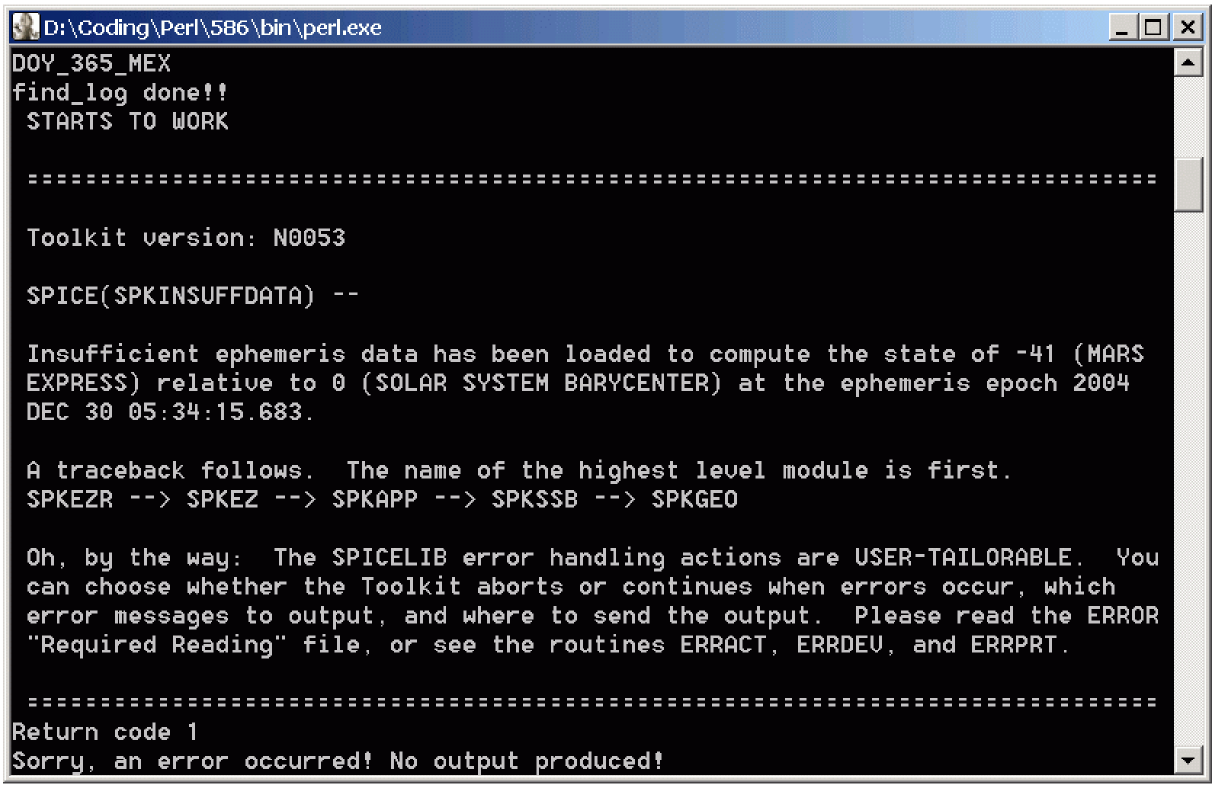
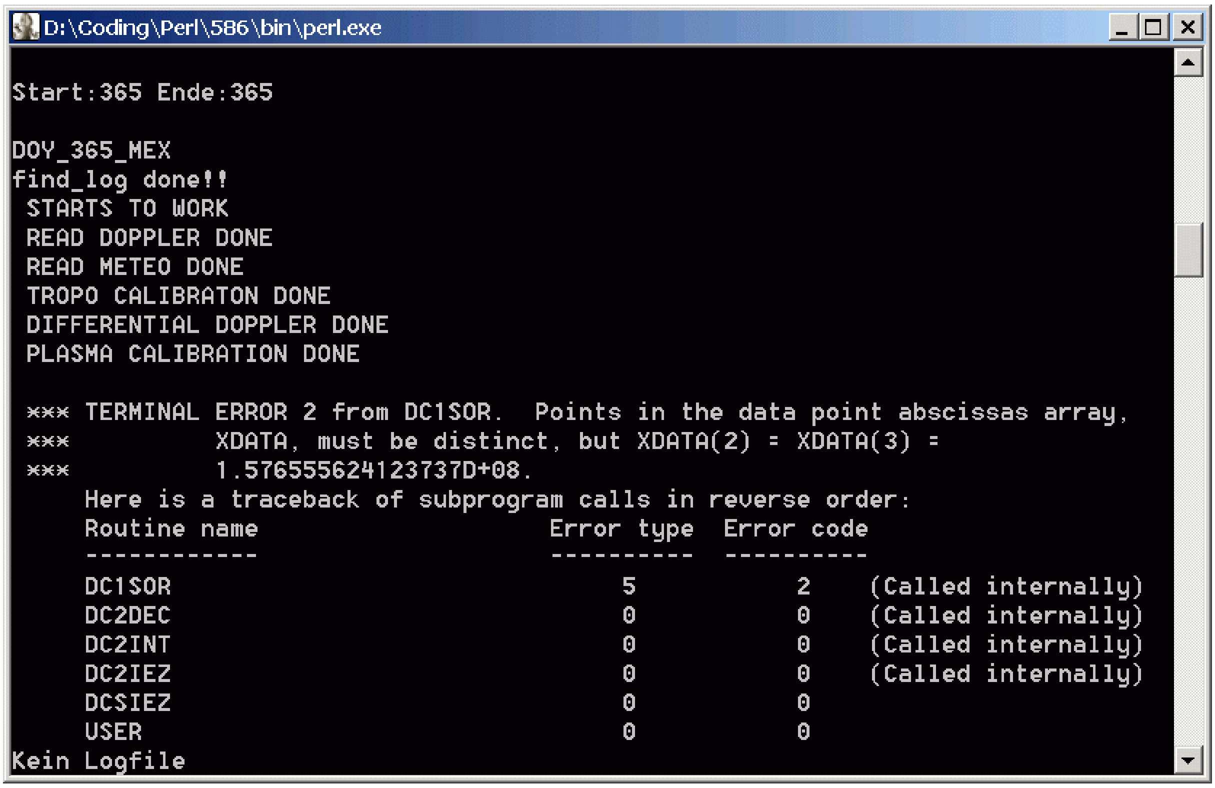


Figure 4-5: Example of an error message if a wrong kernel file is loaded.

- 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.



```
D:\Coding\Perl\586\bin\perl.exe

Start:365 Ende:365

DOY_365_MEX
find_log done!!
 STARTS TO WORK
 READ DOPPLER DONE
 READ METEO DONE
 TROPO CALIBRATON DONE
 DIFFERENTIAL DOPPLER DONE
 PLASMA CALIBRATION DONE

 *** TERMINAL ERROR 2 from DC1SOR.  Points in the data point abscissas array,
 ***          XDATA, must be distinct, but XDATA(2) = XDATA(3) =
 ***          1.576555624123737D+08.
     Here is a traceback of subprogram calls in reverse order:
     Routine name                    Error type  Error code
     ------------                    ----------  ----------
     DC1SOR                               5           2    (Called internally)
     DC2DEC                               0           0    (Called internally)
     DC2INT                               0           0    (Called internally)
     DC2IEZ                               0           0    (Called internally)
     DCSIEZ                               0           0
     USER                                 0           0
Kein Logfile
```

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:

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

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

One-way case

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

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

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

<u>Two-way case:</u>

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

<u>needed is</u>

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

therefore

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

or

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

with

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

and therefore the sky frequency is

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

APPENDIX B

Computation of the plasma correction using the differential doppler

The differential doppler is computed via

$$\delta f = f_{S,antenna}\Big|_{tropo\_corrected} - \frac{3}{11} f_{X,antenna}\Big|_{tropo\_corrected} \qquad (1.12)$$

or

$$\delta f = -\frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\} f_S \frac{dI}{dt} \qquad (1.13)$$

therefore the temporal change in electron content is

$$\frac{dI}{dt} = -\left\{\frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\right\}^{-1} \frac{\delta f}{f_S}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\}^{-1} \qquad (1.14)$$

the plasma correction for S-Band is

$$f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} + \frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\frac{1}{f_S}\frac{dI}{dt} \qquad (1.15)$$

and for X-Band

$$f_{X,antenna,cal} = f_{X,antenna}\Big|_{tropo\_corrected} + \frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\frac{1}{f_X}\frac{dI}{dt} \qquad (1.16)$$

If equation (1.14) is inserted into (1.15)

$$f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} + \frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\frac{1}{f_S}\left(-\left\{\frac{1}{2c}\frac{1}{4\pi^2}\frac{e^2}{m_e\varepsilon_0}\right\}^{-1}\frac{\delta f}{f_S}\left\{\frac{1}{f_S^2} - \frac{1}{f_X^2}\right\}^{-1}\right)$$

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

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

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

Therefore equation (1.15) ca be written as

$$\boxed{f_{S,antenna,cal} = f_{S,antenna}\Big|_{tropo\_corrected} - \delta f \, \frac{121}{112}} \quad (1.18).$$

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

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

Using equation (1.17)

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

therefore equation (1.16) can be written as

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

APPENDIX C

Computation of the predicted X/S-band frequency

Expected frequency at the receiving groundstation at received time (Columns 2-4 in Table 3-2 and 3-3). The calculation includes geometrical effects (relative positions and motions of ground station and spacecraft, including Earth rotation and light time adjustments) and a model-based correction for one- or two-way (as appropriate) propagation through the Earths neutral atmosphere and through the Earths ionosphere:

$$f_{pred} = f_T + \Delta f_{Doppler} + \Delta f_{Atmosphere} + \Delta f_{Ionosphere}$$

where
f_{pred}: predicted frequency
f_T: transmitted frequency (by the uplink groundstation or the spacecraft)
$\Delta f_{Doppler}$: Doppler frequency shift due to relative velocity between transmitter and receiver
$\Delta f_{Atmosphere}$: correction for the effect of propagation through the Earth atmosphere
$\Delta f_{Ionosphere}$: correction for the effect of propagation through the Earth ionosphere

The frequency dependend Doppler shift is computed according (Andert T., 2010[1])

$$\delta f = \frac{\Delta f_{Doppler}}{f_T} = 1 - \frac{1 - \mathbf{n\beta_R} + \frac{1}{2}|\boldsymbol{\beta}_\mathbf{R}|^2 - \frac{\Phi_R}{c^2}}{1 - \mathbf{n\beta_T} + \frac{1}{2}|\boldsymbol{\beta}_\mathbf{T}|^2 - \frac{\Phi_T}{c^2}}$$

where
$\Delta f_{Doppler}$: Doppler frequency shift with $\Delta f = f_T - f_R$ where f_T is the transmitted frequency and f_R is the received frequency
n: the normalized vector from transmitter at transmission time t_T to receiver at receiving time t_R
$\beta_{T/R}$: the normalized velocity of transmitter/receiver with $\beta_{T/R} = v_{T/R}/c$, where $v_{T/R}$ is the velocity of the transmitter/receiver at the time of transmission/reception $t_{T/R}$
c: speed of light
$\Phi_{T/R}$: gravity potential of the Sun and the planet in which sphere of influence the transmitter/receiver is located

If the receiver or transmitter is located on Earth the centrifugal potential from Earth rotation should also to be taken into account when computing $\Phi_{T/R}$.

[1] Andert T., *Masses of Small Bodies: Mass estimation of small solar system bodies using Radio Science data from close flybys, PhD Thesis, University of Cologne, 2010.*

The Doppler shifted frequency then is:

for 1-way uplink measurements

$$f_{Doppler,received} = f_{Up} \cdot \left(1 - \delta f_{Up}\right)$$

for 1-way downlink measurements

$$f_{Doppler,received} = f_{Down} \cdot (1 - \delta f_{Down})$$

for 2- or 3-way measurements

$$f_{Doppler,received} = k \cdot f_{Up} \cdot \left(1 - \delta f_{Up} - \delta f_{Down} + \delta f_{Up} \cdot \delta f_{Down}\right)$$

$f_{Up/Down}$: transmitted frequency by the uplink groundstation or the spacecraft (see Columns 7 and 8 in Table 3-2 and 3-3)
k: transponder ratio